Propulsion Optimisation in Long Combinations

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1 Introduction

The addition of electric propulsion on axles other than the conventional engine-propelled axles in long combinations is necessary to meet power and gradeability requirements as well as stability performance in lateral manoeuvres. But, the choice of axles is to be well-motivated by means of evaluating the vehicle behaviour and productivity in all possible cases and optimising the configuration for customer productivity and OEM sales offering.

In this case, the above problem is sought to be solved in the following briefly enumerated steps:

- Express vehicle productivity as a cost function considering the effect of addition of propulsion in terms of chosen design variables
- Set up an optimisation formulation to arrive at the right design variable set. The optimisation scheme chosen in this case is an evolutionary algorithm.
- Couple the optimisation formulation with a well-defined, yet simple and hence easy-to-execute vehicle model in order to evaluate vehicle parameters that influence the productivity cost function.
- Apply the above generic algorithm to two specific target configurations - The A-double and the Bi-articulated city bus and arrive at the optimal propulsion configuration for specific pre-defined missions.

2 Design variable definition

The choice of design variables and design parameters must be made before the objective formulation is taken up. Design variables are here defined as those configuration features that will be evaluated and determined as a result of the optimisation runs. Design parameters are defined as those configuration features that closely influence the productivity function but remain constant for a chosen population. With this distinction set up, the design variables can be briefly as listed below. It must be noted that the list is not exhaustive at the time of writing this report.

- Number of axles to be propelled in the combination (excluding the tractor axles)
- Motor sizing to match required tractive force
- Total size of energy buffers required
- Size of energy buffers for each trailing unit
- Differential sizing

The design parameters currently identified are listed below:

- Choice between in-wheel / single motor propelled axles
- Choice of energy management algorithm (EMA)
- Choice of conventional engine model (D11 / D13 / D16)
- Choice of hub-motors versus differential-driven trailer axles
- Battery and motor prices
- Fuel price

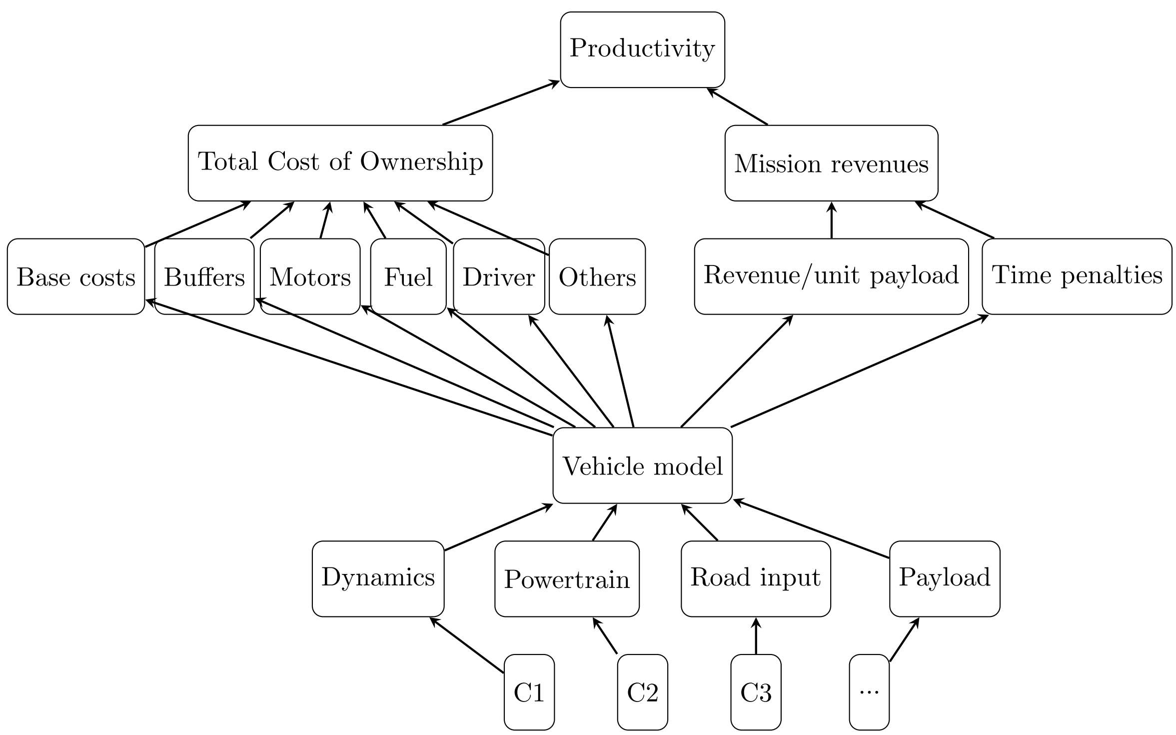
- Battery performance type in terms of end-of-lifetime State of Health (ΔSoH^{econ})
- Average yearly mileage for given combination / average number of trips per year
- Mission - route and speed profiles
- Type of payload and cost of transportation per kilometer per ton (or per unit volume)
- Driver costs
- Yearly maintenance costs
- Markup percentage (?)
- Electricity price per kWh and fixed cost of setting up charging stations in case of plugins

It must be noted that the energy management algorithm may itself be set up as an individual sub-optimisation schedule with individual design variables and parameters.

3 Process flow

The goal, as discussed earlier, is to optimise the productivity function of the combination for the given mission subject to performance based characteristic constraints. As a short marker here, it must be noted that this renders the problem ideally suited for a model predictive control approach, given the mission and speed profiles.

The productivity function is derived from the vehicle in the manner described in the flowchart below:



The optimisation schedule is similar: Each member of the population is evaluated for productivity through the vehicle model and the GA delivers the fittest individual with the maximum productivity.

4 Productivity definition

The productivity has been defined as a simple function of the costs and revenues as follows:

$$Productivity = \frac{MissionRevenue}{MissionCost} \tag{1}$$

As can be seen, the productivity is desired to be as large as possible.

There are several components that contribute to the mission cost. Each of these have a fixed and variable / operating component. They are seperately described below:

4.1 Base combination cost

The combination without the electric axles consists of the tractor unit, dolly, B-semitrailer and the semi-trailer.

$$P_{tractor} = P_{chassis} + P_{engine} + P_{transmission} + P_{RAT}(€) \tag{2}$$

$$P^{purch}_{tractor} = markup * P_{tractor}(€) \tag{3}$$

$$Cost^{purch}_{combination} = P^{purch}_{tractor} + P_{dolly} + P_{BST} + P_{ST}(€) \tag{4}$$

The mission operating cost due to just the combination can be written as

$$Cost^{operating}_{combination} = annuit(Cost^{purch}_{combination})(€) \tag{5}$$

We now elaborate the costs due to electrification of additional axles.

4.2 Batteries / Buffers

The buffer cost is best expressed in terms of cost per kWh of energy stored in the buffers. The buffer size is a design variable and the cost can be simply expressed as:

$$P_{battery} = Size_{buffer} \times Price_{perkWh}(€) \tag{6}$$

$$P^{purch}_{battery} = markup \times P_{battery}(€) \tag{7}$$

The total fixed cost of the buffers including maintenance is:

$$Cost^{Fixed}_{Battery} = \frac{annuit(P_{battery})}{L_{mission}}(€/km) \tag{8}$$

$$\mu^{mission}_{battery-replacement} = \mu^{econ}_{battery-replacement} \times \frac{L_{mission}}{L_{econ}}(units) \tag{9}$$

where,

$$\mu^{econ}_{battery-replacement} = floor(\Delta SoH^{econ} \times \frac{L_{mission}}{L_{econ}}) \times \frac{L_{econ}}{L_{mission}}(units) \tag{10}$$

The end-of-economic-lifetime state of health ΔSoH^{econ} and total lifetime distance $L_{mission}$ are design parameters. The motivation for these are drawn from [2]. Thus, the battery operating cost can be expressed as

$$Cost^{Operating}_{Battery} = Cost^{Fixed}_{Battery} \times \mu^{mission}_{battery-replacement}(€/km) \tag{11}$$

Thus, (8) and (11) together represent battery costs that add to the total cost in the productivity function:

$$Cost_{Battery} = Cost^{Fixed}_{Battery} + Cost^{Operating}_{Battery}(€/km) \tag{12}$$

4.3 Electric transmission

Since the motors can be said to transfer power from the energy buffers to the wheels, the total power rating of all the motors put together may not exceed that of the buffers. The choice of hub-motors (in-wheel motors) naturally suits torque vectoring in order to improve the lateral (yaw) performance of individual units. The more economical installation of a single motor coupled with a differential and drive shafts is also evaluated in this model through a switch choice.

The cost function for the electric drive is thus written as:

$$Cost_{electric-drive}^{fixed} = \frac{annuit(markup \times P_{electric-powertrain})}{L_{mission}} (€/km) \tag{13}$$

where,

$$P_{electric-powertrain} = (n_{electric-machine} \times P_{electric-machine}) + (n_{mechanical-drives} \times P_{mechanical-drives})(€) \tag{14}$$

$$P_{electric-machine} = P_{electric-motor} + P_{auxiliary-equipment}(€) \tag{15}$$

and,

$$P_{mechanical-drives} = P_{differential} + P_{drive-shafts}(€) \tag{16}$$

The auxiliary equipment comprises the power electronics, cooling and other supporting features associated with each motor installation. One does not expect to replace motors during the operating lifetime of the truck-trailer combination. Hence, the operating cost of the electric powertrain is owed to maintenance costs alone.

4.4 Fuel and electricity

Depending on if the combination is a pure hybrid or a plugin, the fuel costs associated with the combination can be differently calculated. This can be incorporated by means a of characterising design variable.

$$P_{fuel} = P_{fuel}^{grid} + P_{fuel}^{plugin}(€) \tag{17}$$

where,

$$P_{fuel}^{plugin} = Mass_{fuel}^{plugin} \times P_{fuel}(€) \tag{18}$$

and,

$$P_{fuel}^{grid} = \frac{E_{grid}}{Q_{fuel}.\eta_{eng}} \times P_{fuel}(€) \tag{19}$$

In the above equations, $Mass_{fuel}^{plugin}$ is obtained from the engine / energy management algorithm (EMA) combination as an output for the given mission.

4.5 Mass and time penalties

The payload carrying capacity of each unit is reduced since the weight of the units are higher due to the additional buffer and electric transmission weight. In order to preserve legal axle loads, the payloads on each unit is reduced by an amount equal to the added mass. Hence,

$$Mass_{reduced-payload} = Mass_{buffer} + Mass_{electricmachine} + Mass_{mechanical} \tag{20}$$

Also significantly, in terms of volume occupied by the buffer,

$$Volume_{reduced-payload} = Volume_{buffer} \tag{21}$$

Depending on the nature of payload being carried, the penalties can be expressed as

$$P_{mass-penalty} = (Mass_{reduced-payload} \times P_{payload-given-mission}) - (\Delta T \times P_{time-bonus})(€) \tag{22}$$

where,

$$\Delta T = \Delta T_{mission} + \Delta T_{charging}(hours) \tag{23}$$

Costs incurred due to time spent in charging the vehicle must be included as downtime costs and find a place in the ΔT component in equation (22). $\Delta T_{mission}$ refers to the reduction in mission time compared to the standard A-Double configuration. Here, $P_{payload-given-mission}$ refers to the returns in € per ton of payload being carried for the given mission.

4.6 Reduction in conventional powertrain cost

The addition of electric propulsion provides the customer the opportunity to choose a lower engine specification at the cost of the electric machine. The goal, of course, remains to motivate this decision and validate the investment to be profitable. Based on the vehicle simulations, if it is found that the engine can be replaced with a lower horsepower one, the reduction in base price of the engine must reflect as a subtraction in the total cost.

$$Cost_{engine-downsizing} = -\Delta P_{engine,base-engine}(€) \tag{24}$$

4.7 Driver Costs

4.8 Revenues

The revenues of the customer can be expressed simply as

$$Revenue = Mass_{payload} \times Earnings_{per-ton}(€) \tag{25}$$

5 Simulation schedule

Several combinations of propulsion choices can be made for the given A-Double combination. Each of these must be evaluated for productivity in the optimisation algorithm. This is done by constructing a virtual vehicle model that corresponds to the configuration chosen for evaluation and simulating the vehicle for the chosen mission (road and load). The outputs of the simulation are fuel consumption, electricity usage, time taken apart from vehicle performance characteristics. The optimisation schedule takes fixed performance characteristics as constraints and uses these to eliminate unsafe or ill-performing combinations from the population.