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Optimal Powertrain Sizing of Series Hybrid Coach Running on Diesel and HVO for Lifetime Carbon Footprint and Total Cost Minimisation

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Abstract: This article aims to calculate, analyse and compare the optimal powertrain sizing solutions for a long-haul plug-in series hybrid coach running on diesel and hydrotreated vegetable oil (HVO) using a co-design optimisation approach for: (1) lowering lifetime carbon footprint; (2) minimising the total cost of ownership (TCO); (3) finding the right sizing compromise between environmental impact and economic feasibility for the two fuel cases. The current vehicle use case derived from the EU H2020 LONGRUN project features electrical auxiliary loads and a 100 km zero urban emission range requiring a considerable battery size, which makes its low carbon footprint and cost-effective sizing a crucial challenge. Changing the objective between environmental impact and overall cost minimisation or switching the energy source from diesel to renewable HVO could also significantly affect the optimal powertrain dimensions. The approach uses particle swarm optimisation in the outer sizing loop while energy management is implemented using an adaptive equivalent consumption minimisation strategy (A-ECMS). Usage of HVO fuel over diesel offered an approximately 62% reduction in lifetime carbon footprint for around a 12.5% increase in overall costs across all sizing solutions. For such an unconventional powertrain topology, the fuel economy-focused solution neither achieved the lowest carbon footprint nor overall costs. In comparison, CO_2-cost balanced sizing resulted in reductions close to the single objective-focused solutions (5.7% against 5.9% for the CO_2 solution, 7.7% against 7.9% for the TCO solution on HVO) with lowered compromise on other side targets (CO_2 reduction of 5.7% against 4.9% found in the TCO-focused solution, TCO lowering of 7.7% against 4.4% found in the CO_2-focused solution).

Keywords: optimal powertrain sizing; co-design optimisation; long-haul coach; plug-in hybrid electric vehicle; series hybrid; HVO; lifetime carbon footprint; total cost of ownership; particle swarm optimisation; powertrain economic feasibility; economic-environmental balance

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1. Introduction

The rising impact of global warming from CO_2 emissions has today become a major concern for future sustainability mobility. The European heavy-duty (HD) long-haul vehicle sector accounts for about one-fourth of its CO_2 emissions from road transport and around 6% of its total carbon footprint [1]. Major standards on heavy-duty vehicle emissions are now being implemented in the European Union (EU) to meet the objectives of the Paris Agreement, with an impetus on fleet-wide average CO_2 emission reduction of new vehicles by 15% from 2025 and 30% from 2030 in comparison to the 2019−2020 reference year [2,3].

Electrification of HD powertrains has shown remarkable potential in reducing overall carbon footprint, including the possibility of completely avoiding tail-pipe emissions using battery electric vehicle (BEV) solutions. However, the adaptation of full-electric propulsion for the long-haul is currently hindered by various technical and practical limitations such as long battery charging time, high cost of pantograph installations and increased vehicle size and weight, leading to lower payload capacity and economic feasibility for the users [4,5]. The hybridisation of conventional HD vehicles is today a more feasible option for reducing long-haul carbon footprint with improved overall powertrain efficiency from the effective usage of multiple power sources, electrification of the cooling system and auxiliary loads, the possibility of energy recuperation through regenerative braking and greater freedom over optimal sizing of the powertrain [6,7]. Depending on the feedstock and production energy source, usage of alternative fuels such as hydrotreated vegetable oil (HVO) could also lower CO_2 emissions due to their renewable nature and potential to increase engine efficiency while decreasing other harmful emissions (NO_x, CO, HC and PM) [8,9]. With more than one power source and load, hybrid powertrains require dedicated energy management tuned for specific types of driving and ambient conditions to operate at high efficiency. Proper sizing of hybrid electric vehicle (HEV) components is thus also influenced by the intended use and operating conditions and has the potential to improve system efficiency significantly [10,11]. Running aspects contribute to a substantial portion of long-haul carbon footprint and costs, while engine efficiency, CO_2 emissions and fuel expenditure from the usage of alternative fuel can also vary considerably. Thus, the optimally sized powertrain solutions for minimising lifetime carbon footprint or total cost of ownership (TCO) of conventional diesel and renewable HVO vehicles could also be significantly different.

The LONGRUN project, funded by the EU Horizon 2020 program, aims at lowering fuel consumption and the environmental impact of HD long-haul vehicles in real driving, including reliance on fossil fuels through the development of new alternative internal combustion engines and hybrid drivelines [12]. Under the LONGRUN project, the current work focuses on calculating, analysing and comparing the optimal powertrain size solutions of a plug-in series hybrid (S-HEV) coach running on diesel and alternative HVO fuel aimed at minimising lifetime CO_2 emissions and the total cost of ownership (TCO) and then exploring a balanced solution considering the environmental as well as economic point of view. As powertrain sizing affects both lifetime carbon footprint and ownership cost from vehicle production and its running differently, the optimum size solution for minimising the two objectives could be different [13]. By calculating, analysing and comparing respective hybrid powertrain sizing solutions, this article could also help explore and find the ideal balance between these two objectives. It will also demonstrate how changing the energy source from conventional to alternative fuel could affect the powertrain sizing aimed at reducing CO_2 impact and overall costs. Lowering the lifetime CO_2 emissions or costs can be considered a trade-off between reducing the impact from production and from well-to-wheel (WTW) fuel consumption over the vehicle's entire life span. Reducing component size leads to lower CO_2 emissions and costs in production. However, it could also hamper the efficient operation of the powertrain over its lifetime, increasing tailpipe emissions and fuel expenditure. On the other hand, optimal powertrain sizing for energy efficiency can significantly lower fuel consumption, thereby reducing emissions and running costs, at the expense of unconstrained production impact [14]. WTW CO_2 emissions from fuel usage comprise the emissions from fuel consumption during vehicle driving, known as tank-to-wheel (TTW) tailpipe emissions, and from fuel production and its transport, known as well-to-tank (WTT) emissions. Thus, a renewable fuel may be considered carbon-neutral, emitting zero TTW tailpipe CO_2, but could still be a source of substantial carbon footprint due to its production process (WTT).

Through comparative life cycle analysis, Eupp et al. have shown the potential of hybridisation in reducing lifetime CO_2 emissions of a heavy-duty parallel hybrid truck saving 4.34 $\mathrm{gCO_{2eq}/t\ km}$ over 1.04 million km mileage [7]. Their break-even analysis has indicated that the HEV solution can compensate for increased electrification-specific production emissions with improved powertrain efficiency after only 15,800 km of running. System design optimisation along with the choice of ideal traction chain topology, eDrive size and gear ratios for an HD battery-electric truck aimed at TCO minimisation has been done by Verbruggen et al. They have implemented a nested loop consisting of particle swarm optimisation (PSO) for powertrain plant sizing and local minimisation control problem for gear shifting and eDrive torque split control [15]. As a part of the ORCA project, Landersheim et al. have demonstrated the effectiveness of plug-in parallel hybridisation and CNG fuel-based ICE application in reducing CO_2 and NO_X emissions along with powertrain TCO for bus application with substantial improvements of 13%, 50% and 10%, respectively [16]. In this project, Tran et al. have further presented a co-design methodology for minimisation of TCO through combined powertrain sizing and control optimisation [17]. Pourabdollah et al. have investigated the impact of modelling details on the problem of optimal FCEV powertrain sizing for minimising TCO and have shown that simplified models based on finding the energy split between power sources can also deliver similar results as the detailed models, although in some specific cases their outcomes may turn out notably different [18]. Series-HEV powertrain sizing optimisation of an urban bus for TCO minimisation considering battery and ICE ageing has been analysed by Junco et al. They have found that battery sizing has a significant impact on the TCO for such applications. For their optimal TCO solution, the battery represented 15% of the overall costs [19]. Spano et al. have proposed a powertrain design methodology for a light-duty P2 hybrid vehicle using evolutionary particle swarm optimisation (PSO) for component sizing and dynamic programming for control strategies to minimise fuel consumption and vehicle production cost [13]. Their work has demonstrated a feasible parity in improving fuel economy at the expense of production cost by considering a range of possible minimisation balances while running on real-world mission profiles. The work has also suggested reducing the number of gears by facilitating propulsion using coordinated interaction of the ICE and EM. Murgovski et al. have presented simultaneous optimisation of powertrain energy management and battery sizing for series and parallel plug-in hybrid powertrains using convex optimisation and have indicated that convexification of plant approximations has little influence on optimised sizing and control [20]. Zhou et al. have compared standard accelerated particle swarm optimisation (APSO) with logistic mapping-based chaos-enhanced APSO approach for multi-objective heavy-duty series hybrid powertrain sizing aiming for efficiency improvement and powertrain volume reduction. They have demonstrated better optimisation performance using CAPSO with a lower mean value of cost function and greater ability to find consistent global optimal solutions. Their sensitivity analysis has suggested that generator size (engine displacement) is a crucial parameter for efficient energy management, whereas the size of ultra-capacitor energy storage showed the least importance. For volume reduction, the ultra-capacitor size showed the highest sensitivity, whereas the battery size had the least effect [21].

Powertrain sizing optimisation and analysis using a co-design approach for long-haul series hybrid coach focusing on lifetime CO_2 emissions, TCO minimisation and finding a balanced solution between the two objectives have not been previously seen in the literature. Additionally, switching the fuel type from conventional diesel to alternative HVO and analysing its effect on the baseline and optimally sized powertrain solutions for fuel efficiency, carbon footprint, and TCO could be of high interest for future research on alternative fuel integration and HEV design activities. The remainder of this article first expands on the long-haul coach vehicle use case, series hybrid powertrain layout, the VECTO derived mission profile under consideration and the assumptions for the different fuel applications (diesel and HVO). The nested co-design optimisation methodology considered in this work along with chosen design variables, powertrain modelling methodology and desired minimisation objectives including fuel consumption, lifetime CO_2 emissions, TCO and environmental-economic balanced reduction are then discussed. Various solutions of the sizing optimisation and their effect on the main objective as well as other desired targets are compared for the two fuel cases. This is followed by a discussion on the proposed CO_2 cost-balanced solution aiming for an acceptable compromise between minimising environmental impact and lifetime costs. Finally, the conclusion of this activity is stated, along with future perspectives.

2. Coach Use Case

The plug-in series hybrid vehicle (S-HEV) coach has been referred to from the LONGRUN H2020 project and features a 100 km range zero urban emission zone (ZUEZ) capability through battery electric-only operation and electrically operated low voltage cooling systems, auxiliaries and heating, ventilation and air conditioning (HVAC) loads. The key vehicle performance requirements of the S-HEV coach considered for this sizing activity have been given in Table 1, whereas Table 2 lists the main vehicle specifications and Figure 1 the cell characteristics.

Table 1. Vehicle key performance requirements used for defining powertrain sizing constraints.

Specification	Value
Acceleration 0–100 km/h (s)	45
Gradeability from standstill (%)	30
Gradeability at 15 km/h (%)	13
Gradeability at 70 km/h (%)	3
Gradeability at 100 km/h (%)	2
Maximum speed (km/h)	100 (80 in ZUEZ)

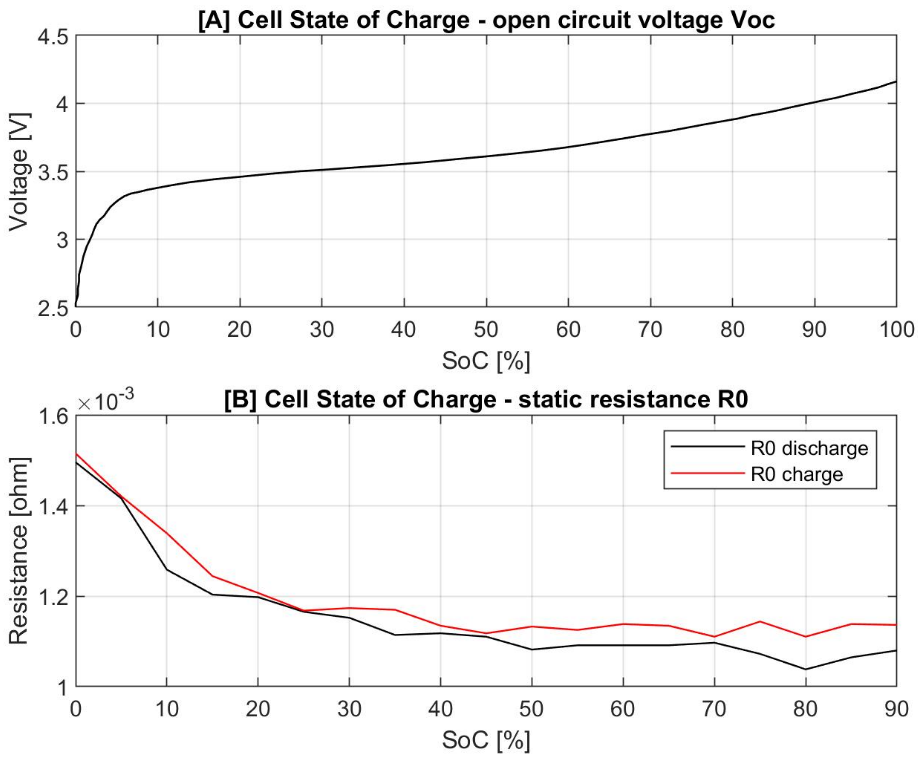

Figure 1. Li-ion NMC cell (**A**) open circuit voltage and (**B**) charge/discharge static resistance.

Table 2. Series hybrid coach use case vehicle specifications.

Specification	Value
Vehicle mass (kg)	19,500
Drag coefficient × front area Cd.A (-m^2)	4.35
No of wheels (-)	6
Wheel radius (m)	0.51
Wheel rotational inertia (kgm^2)	15.5
Wheel rolling resistance coefficient (-)	0.0056
Nominal HV battery, DC link voltage (V)	650
Differential torque drop (Nm)	VECTO map
Differential rotational inertia (kgm^2)	1.25
Differential reduction ratio (-)	2.71:1
Gearbox inertia (kgm^2)	1.45
Cell type (-)	Li-ion NMC
Cells in series (-)	180
Cell charge capacity (Ah)	50
Cell open circuit voltage (V)	Figure 1
Cell internal resistance (Ω)	Figure 1
Cabin volume (m^3)	50
No of passengers (-)	60
HVAC recirculation rate (%)	90
HVAC blower flow rate (m^3/s)	0.75

2.1. Series Hybrid Powertrain

The current plug-in series-HEV powertrain features an electric drive with a 3-speed transmission comprising of a low gear for large wheel torque requirements during high gradeability, vehicle launch and acceleration; a high gear for maximum vehicle speed; a middle gear for efficient motor operation and consistent maximum wheel torque delivery in the EM constant power zone (Section 3.2). In the current context with battery state of charge sustaining operation after ZUEZ driving, the primary source is a range extender comprising of an internal combustion engine-generator combination, while the secondary source is a high voltage (HV) battery pack used for low load, boosting, load levelling and ZUEZ operation while also facilitating storage and reuse of recuperated energy from regenerative braking (Figure 2).

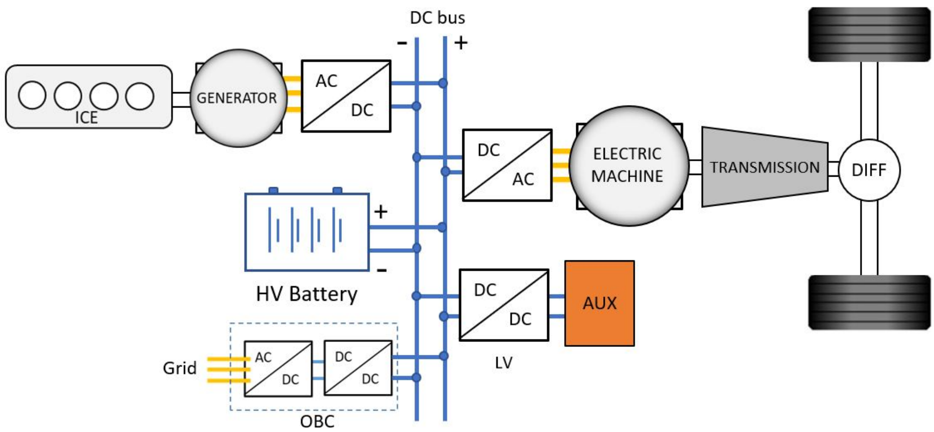

Figure 2. Plug-in series hybrid powertrain architecture used in the ZUEZ long-haul coach use case.

The baseline dimensioning of eDrive and gear ratios (described in Section 4) for comparing optimised sizing solutions has been set to fulfil vehicle key performance requirements (Table 1) and smooth running on VECTO interurban (Section 2.2) and coach cycles while also considering minimal production impact. Initial sizing of the ICE−generator range extender and HV battery have been made following manufacturer recommendations and required ZUEZ range while assuring SoC sustaining for urban and highway driving under extreme ambient conditions. The above constraints of vehicle key performance requirements, SoC sustaining, driveability and 100 km ZUEZ range have been validated on a detailed distance-based forward powertrain model depicting real-world operation.

2.2. Drive Cycle

Thr interurban mission profile derived from the European Commission VECTO simulation tool comprising urban and interurban driving scenarios has been used for the current optimal powertrain sizing activity [22,23]. Figure 3 shows distance-based interurban speed recommendations and actual speed following VECTO acceleration limits along with road gradient and the power drawn by the eDrive and auxiliary loads (baseline sizing dimensions given in Section 4).

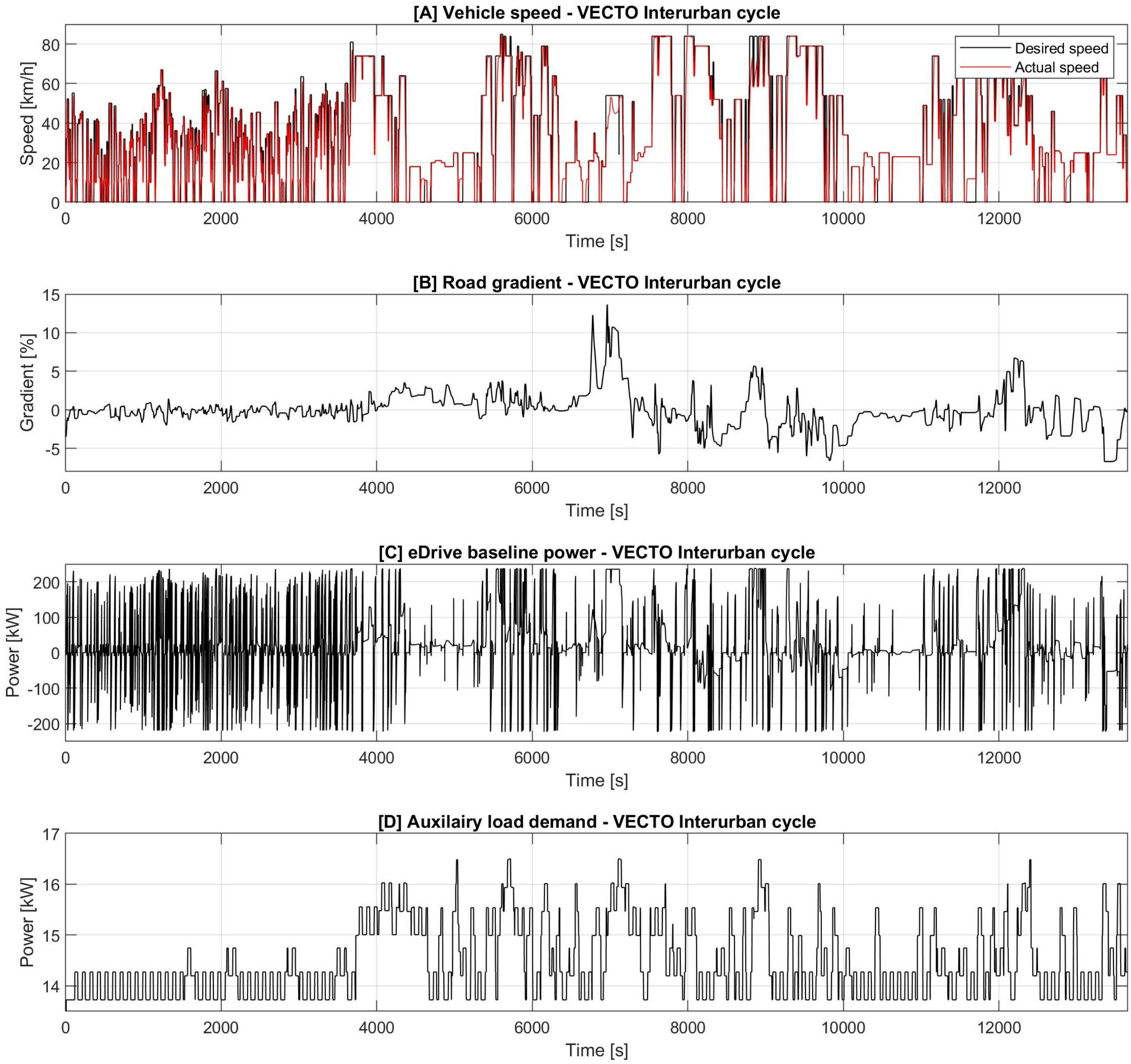

Figure 3. VECTO interurban (**A**) cycle speed recommendation and actual speed from distance-based forward model, (**B**) road gradient, (**C**) eDrive power for baseline configuration (240 kW) and (**D**) auxiliary load including HVAC and cooling.

2.3. Fuel

Changing the energy source from diesel to HVO will affect well-to-wheel (WTW) carbon footprint and running costs from vehicle lifetime usage. This is considered a consequence of varying tank-to-wheel (TTW) and well-to-tank (WTT) emissions, changing lower heating values (LHV), fuel density and cost, and also from a slight variation in the ICE brake thermal efficiency when running on HVO instead of diesel (Table 3). Thus, for both CO_2 emissions and TCO-based sizing optimisation cases, the ICE brake thermal efficiency map has been modified from diesel to HVO after referring to the literature review with slightly greater efficiency at higher load points [8,9,24] (Figure 4).

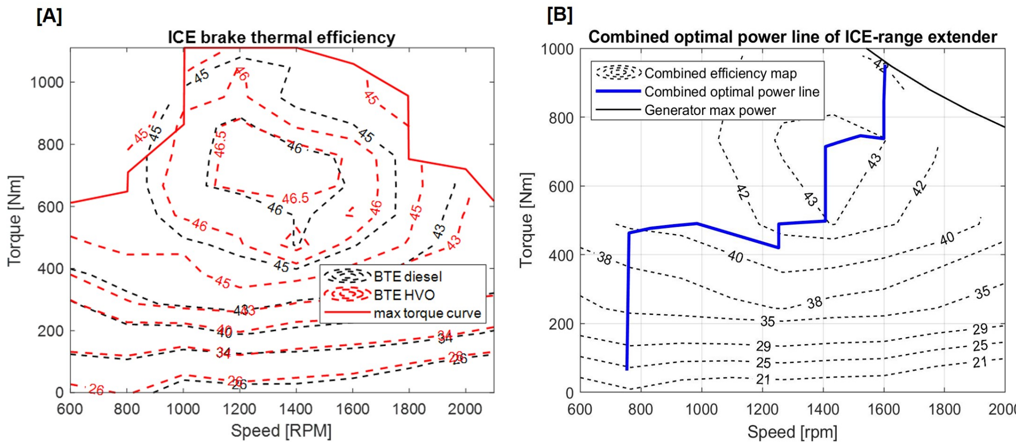

Figure 4. (**A**) Diesel and HVO ICE brake thermal efficiency comparison: map modified for HVO fuel with slightly greater efficiency at higher loads. (**B**) ICE—generator combined efficiency map with the optimal power line to be followed for minimal fuel consumption (diesel and HVO).

Table 3. Fuel properties considered for diesel and HVO.

Property	Diesel	HVO
Density (g/L)	837 [25,26]	781 [9,27]
Lower heating value (MJ/kg)	42.75 [25,28]	43.81 [9,27]
Production CO_2 WTT (gCO_{2eq}/L)	762.15 [29]	1094.9 [29,30]
Consumption CO_2 TTW (gCO_{2eq}/L)	2640 [26]	0

3. Powertrain Sizing Optimisation

The optimal S-HEV powertrain sizing aimed at lifetime carbon footprint (CO_2), the total cost of ownership (TCO) or fuel consumption minimisation is achieved through a fair comparison of various feasible size solutions, which is assured by consistent performance of energy management strategy across the complete range of sizing iterations before their evaluation [15]. This is achieved through a co-design approach wherein a nested loop comprising the outer sizing stage and the inner powertrain energy management stage are run in iterations [17,31].

3.1. Optimisation Methodology

In the chosen co-design optimisation approach, the control design is nested within the plant design, requiring its consistent performance for a given solution before comparing the minimal cost function for that size with other feasible options to find the final powertrain sizing optimum (Figure 5) [32].

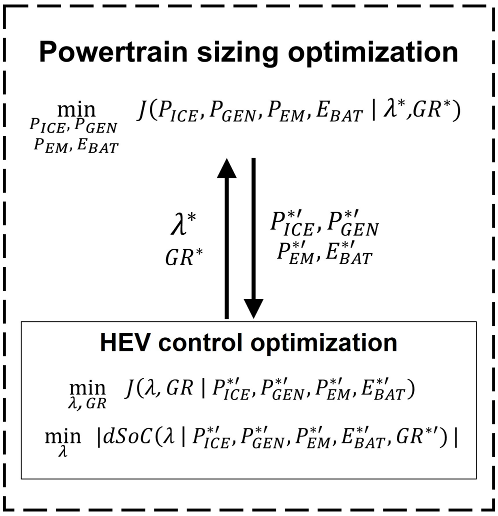

Figure 5. Nested powertrain co-design approach with integrated component sizing and energy management optimisation. $*$ represents optimal values while $*'$ shows that the values may or may not be optimal.

In the inner control loop, the optimal gear shifting of the traction chain is assured through a heuristic energy optimal shift logic considering minimisation of eDrive losses by choosing the gear GR, which lands the eDrive operating points in the highest efficiency zone for a given wheel speed and wheel torque request while respecting limits of maximum eDrive torque, speed and also avoiding gear hunting [33–35]. An example of such a gear shifting logic dependent on wheel speed and torque demand is shown in Figure A1.

$$\begin{aligned} \min_{GR} \quad & \omega_{em}\, T_{em}\, (1 - \eta_{EM}(\omega_{em}, T_{em})) \\ \text{s.t.} \quad & 1 \leq GR \leq 3 \end{aligned} \tag{1}$$

Optimal usage of the two on-board energy sources (ICE−generator range extender and HV battery) for minimisation of overall fuel consumption L_{fequi} is assured by the equivalent consumption minimisation strategy (ECMS), which has been known to deliver close to optimal hybrid powertrain energy management with the possibility of real-time online implementation [36–38]. The ECMS online strategy first discovered by Pagnelli et al. is based on the global Pontryagin's minimisation principle (PMP) applied for local minimisation of instantaneous equivalent fuel consumption [39–41].

$$P_{fequi} = P_f(P_{gen}) + \lambda\, P_{batt}(P_{elec}, SoC)\, k_c \tag{2}$$

Here, P_f and P_{batt} are the actual instantaneous fuel power consumption and the actual battery power expenditure depending on the generator power demand P_{gen}, battery power demand P_{elec} and SoC (affecting battery losses). P_{fequi} is the instantaneous hamiltonian to be minimised, which in this case is the equivalent fuel power consumption. First, an optimal static power split map for the sizable range extender (P_{gen}) and battery (P_{elec}) is calculated through offline PSO based calculations for a range of possible positive power demands (P_{em} and P_{aux}) and battery conditions (changing SoC, static resistance and terminal voltage) (Figure 6). The scope of various possible operating scenarios is covered by considering a broad span of possible equivalence factors λ (battery equivalent costates) [42]. To maintain the simplicity of ECMS implementation, a single equivalence factor λ has been considered for both the battery charging and discharging conditions. Figure 6 shows that there is a difference in the optimal offline ECMS power split calculation between diesel and HVO cases on account of the ICE brake thermal efficiency and fuel properties variation considered for this activity (Figure 4).

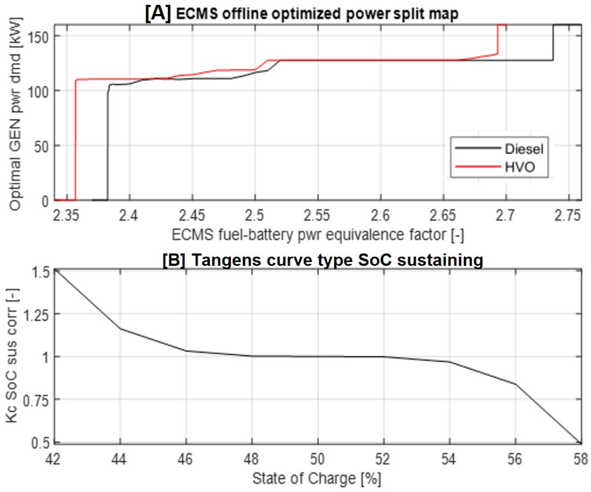

Figure 6. ECMS offline calculation: (**A**) optimal range extender electrical power demand for diesel and HVO cases depending on varying SoC equivalence factor, (**B**) tangens curve of SoC-sustaining correction factor.

The offline optimised power split map is then implemented in the full powertrain model used for sizing optimisation (online), with the end of mission battery SoC sustaining targeted to find the most fuel-efficient fixed value ECMS equivalence factor λ for a specific cycle [37]. Safety against battery overcharging/discharging and SoC sustaining is further assured using a less intrusive tangens type SoC equivalence factor adaption coefficient k_c (Figure 6) [42–44]. Highly intrusive control on SoC sustaining is avoided to let the ECMS strategy work in the most efficient manner, which may lead to a slight variation in end-of-cycle SoC (Section 4.6). Instead, the corresponding effect on fuel usage is taken into consideration by calculating equivalent fuel consumption based on SoC surplus or depletion (Sections 3.3.1 and 3.4.4).

Once the co-design framework reaches optimal energy management for a given powertrain size (SoC sustaining), the particle swarm optimisation algorithm (PSO) is implemented in the sizing stage for comparing the optimally tuned size iteration results and finding the best possible powertrain dimensioning in a predefined search space (Section 3.2) [11,15,45,46]. The PSO algorithm, initially devised by Kennedy and Eberhart, is based on the social behaviour of animals, such as that seen in ant colonies and bird flocking [47]. A group of particles within a search space share information about their last found best solution and then concentrate the search around the region of the best-found solution within the group. The process is repeated until the group converges to the optimal solution within the given search space [41]. The iterative particle displacement, velocity and communication between particles are the main tuning characteristics of particle swarm optimisation. The current search space is dimensioned by the number of chosen design variables (six in this case) and their corresponding upper and lower bounds (Section 3.2) [48].

3.2. Design Variables

Powertrain size optimisation for minimising lifetime CO_2 emissions or TCO means finding the best compromise among different component size combinations that yields the ideal balance between production and vehicle running impacts over its complete lifespan. ICE−generator (range extender) and eDrive size in terms of their maximum power output $P_{ICE}-P_{GEN}$, P_{EM} and HV battery size in maximum energy capacity E_{BAT} form the scalable design variables affecting both vehicle production and lifetime operation aspects. Range extender and eDrive maximum power outputs are varied by vertically scaling the maximum torque line shown in Figure 7, and battery charge capacity (Ah) is sized by changing the number of cell strands connected in parallel (n_p) and cell charge capacity (C_{max}). On the other hand, transmission gear ratios are only assumed to affect the traction chain efficiency (running emissions and costs), while their impact on production costs will be neglected as the transmission type has been fixed in the vehicle use case topology (Section 2).

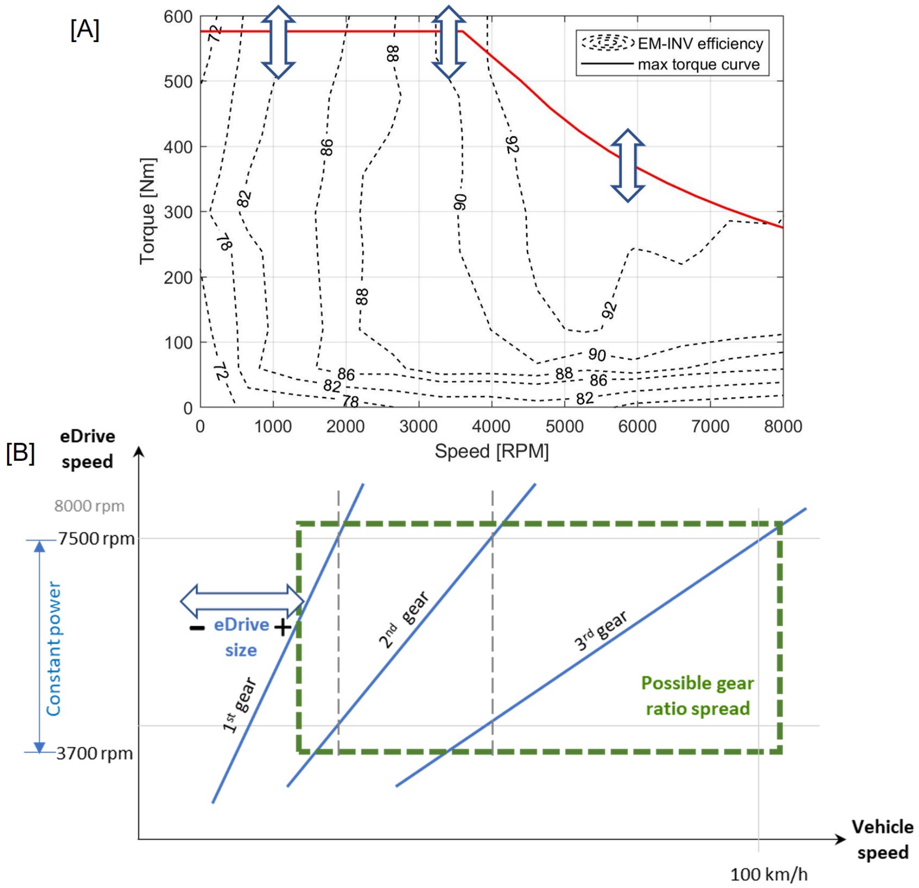

Figure 7. (**A**) eDrive electrical efficiency map with sizing based on maximum torque curve. (**B**) Traction chain sizing methodology including the effect of eDrive scaling on possible gear ratio search space.

The upper limit of the ICE−generator range extender size (P_{ICE}, P_{GEN}) is set to match the maximum possible eDrive size considering manufacturer recommendations, while the lower limit is set by the ability to sustain battery SoC at the end of VECTO interurban and coach drive cycles (Table 4). The upper bound of the HV battery size E_{bat} (240 kWh) is added from vehicle integration constraints and manufacturer recommendations, while the lower bound (160 kWh) is set by the previously discussed 100 km ZUEZ urban driving range requirement, which has been tested on the detailed distance-based forward simulation model under extreme ambient conditions (40 °C).

Table 4. Component sizing parameters, constraints and interdependencies (design variable limits). Underlined values represent fixed (hard) constraints and bold values show design interdependencies.

Component	Lower Bound	Upper Bound
ICE-range extender (kW)	120	480
battery (kWh)	160	240
eDrive (kW)	**240**	480
Gear ratio 1 (-)	**17.269:1**	22:1
Gear ratio 2 (-)	**7:1**	**10:1**
Gear ratio 3 (-)	**4:1**	5.055:1

The upper bound for the eDrive size (P_{EM}) is set considering manufacturer feasibility and a general understanding of coach traction power requirements, while the lower limit comes from the minimal peak wheel torque and power constraints tested on the distance-based forward model to satisfy vehicle key performance requirements (Table 1) and acceptable operation on VECTO mission profiles (Figure 3) [15]. The lower limit of eDrive size (maximum torque) is also linked with the value of the first gear ratio to support the peak wheel torque requirement used for climbing large gradients, vehicle launching and acceleration (Tables 1 and 4) [49]. The upper limit of the third gear ratio is added for the desired maximum speed of the eDrive during highway operation (set to 7500 RPM for 100 km/h considering eDrive efficiency from Figure 7).

The spread of the three gear ratios has to be limited to assure consistent and uninterrupted delivery of maximum wheel torque (maintain eDrive operation in constant power region) when shifting between gears (Figure 7). Thus, the lower bound of the middle gear ratio is dependent on the selected value of the third gear ratio, while the upper bound of the middle gear ratio depends on the chosen value (lower bound) of the first gear ratio, which in turn is affected by the chosen eDrive size (Table 4) [50]. Choice of the middle gear ratio also affects the lower bound of the third gear ratio (rotational speed of the eDrive during high-speed cruising) for maintaining the above-mentioned smooth operation. In general, a larger eDrive size has been found to relax the search space of the first gear and thus also the middle and third gear ratios. This helps maintain continuous maximum wheel torque delivery between gear changes and avoid gear hunting while also better controlling the placement of eDrive operating points towards high-efficiency zones. Optimal eDrive sizing will shift the operating points vertically in the efficiency map and improve the scope of regenerative braking, while gear ratio tuning will help in better operating point placement, both vertically and horizontally in the eDrive efficiency map (Figure 7 and Section 4.7).

Table 4 details the upper and lower bounds of the discussed six sizing design constraints for the current S-HEV coach powertrain. Underlined values represent hard constraints, while bold values present the above-discussed constraint interdependencies between design variables. The above-discussed configuration with lower size bounds of different powertrain components (Table 4) has been tested on the distance-based powertrain model to assure vehicle key performance requirements (Table 1) and desired speed following capability on VECTO mission profiles (Figure 3).

3.3. Minimisation Objectives

To analyse a wide range of powertrain sizing configurations, the minimisation objectives and the impact of their pursuit on other important outcomes, lowering of fuel consumption, carbon footprint, and total cost of ownership have been considered and compared to explore a compromise between reducing lifetime environmental impact (CO_2) and costs (TCO). The size of the S-HEV coach's main powertrain components will be tuned to balance the impact of production and fuel consumption aspects while assuring the key vehicle performance (Table 1). We will now thus consider powertrain lifetime CO_2 emissions ($pCO_{2_{tot}}$) and powertrain total cost of ownership ($pTCO$) instead of vehicle level quantities to be able to more clearly compare the effect of different component sizes on powertrain optimisation [17]. Due to the nature of the coach vehicle usage and interurban cycle, a lifetime mileage of 550,000 km has been considered for CO_2 and TCO minimisation following VECTO assumptions with one expected battery replacement at 275,000 km due to its ageing [7,22].

3.3.1. Equivalent Fuel Consumption

Fuel consumption minimisation, usually the objective for most powertrain sizing activities, is solely related to improving overall powertrain efficiency and thus presents a case for comparison against other sizing solutions in this work, considering its complete neglect of production aspects. Although the S-HEV is expected to sustain initial battery SoC at the end of the interurban drive cycle, equivalent fuel consumption L_{fequi} is chosen for minimisation to make a fair comparison between size solutions and is calculated by considering the value of the SoC surplus/depletion ($dSoC$) and the fuel equivalent energy it holds for propelling the vehicle. Theoretical battery SoC usage tested to run the vehicle in full electric mode over the entire mission profile ($mSoC$) is used to find this equivalent fuel consumption (with battery operation in the usual HEV SoC operating range). Here, L_f is the actual fuel consumption ignoring battery SoC deviation at the end of the drive cycle.

$$L_{fequi} = L_f \left(1 + \frac{dSoC}{mSoC - dSoC}\right) \quad (3)$$

3.3.2. Lifetime Carbon Footprint Minimisation (pCO_2)

Minimising pCO_2 emissions over the entire vehicle lifespan ($pCO_{2_{tot}}$) will consist of finding the optimum powertrain size, which could give the ideal compromise between reducing emissions from component production and from the efficient running of the powertrain. Decreasing component size will in reduce pCO_2 emissions from their production $pCO_{2_{Prod}}$, but may hamper efficient powertrain operation, increasing fuel consumption and running emissions $pCO_{2_{Conso}}$, whose impact on a heavy-duty vehicle could be substantial depending on the long lifetime mileage.

$$pCO_{2_{tot}} = pCO_{2_{Prod}} + pCO_{2_{Conso}} \quad (4)$$

Carbon footprint impact factors for individual component manufacturing, CF_{ICE}, CF_{EM}, CF_{GEN} and CF_{BAT} (Table 5), along with their respective sizes, P_{ICE}, P_{EM}, P_{GEN} and E_{BAT} (rated power and energy capacity), are used to calculate the emissions impact from powertrain production $pCO_{2_{Prod}}$.

$$pCO_{2_{Prod}} = CF_{EM}\, P_{EM} + CF_{ICE}\, P_{ICE} + CF_{GEN}\, P_{GEN} + 2\, CF_{BAT}\, E_{BAT} \quad (5)$$

Equivalent fuel consumption over VECTO interurban mission profile L_{fequi}, well-to-wheel carbon footprint comprising of WTT impact factor from fuel production, distribution ($CF_{FuelWTT}$) and TTW tail pipe emissions impact factor ($CF_{FuelTTW}$) (Table 3) along with vehicle lifetime mileage D_{life} are together used to calculate vehicle running carbon footprint over entire lifespan $pCO_{2_{Conso}}$.

$$pCO_{2_{Conso}} = (CF_{FuelWTT} + CF_{FuelTTW})\, L_{fequi}\, D_{life} \quad (6)$$

Table 5. Component production carbon footprint impact factors.

Component	Carbon Footprint (gCO_{2eq}/-)	Power/Weight Ratio (kW/kg)
ICE (gCO_{2eq}/kg)	7778 [51]	0.92
eDrive (gCO_{2eq}/kg)	8462 [51]	2
Generator (gCO_{2eq}/kg)	8462 [51]	2
Battery (gCO_{2eq}/kWh)	80,000 [52,53]	-

3.3.3. Total Cost Minimisation ($pTCO$)

Reducing powertrain total cost of ownership ($pTCO$) comprises lowering the cumulative capital expenditure from powertrain production ($pCAPEX$) and operating expenditure from fuel consumption ($pOPEX$) over the entire vehicle lifespan [17,54]. The optimal size solution for minimal $pTCO$ will thus come from finding the right balance between decreasing the cost of individual component production through size reduction and lowering lifetime fuel consumption cost by improving S-HEV efficiency through ideal powertrain sizing.

$$pTCO = pCAPEX + pOPEX \quad (7)$$

The complete powertrain efficiency (coming from synchronised functioning of individual subsystems−-eDrive, ICE−generator and HV battery), applied ECMS energy management strategy, varying fuel and component production costs (Table 6) and changing fuel properties between diesel and HVO (Table 3) will together affect the $pTCO$ optimal powertrain size for the two fuel cases.

$$pCAPEX = C_{ICE}\, P_{ICE} + C_{EM}\, P_{EM} + C_{GEN}\, P_{GEN} + 2\, C_{BAT}\, E_{BAT} \tag{8}$$

Here, C_{ICE}, C_{EM} and C_{GEN} are costs per kW of ICE, eDrive and generator whereas P_{ICE}, P_{EM} and P_{GEN} are their respective rated power levels indicating component size (design variables) while running the sizing optimisation. C_{BAT} and E_{BAT} are the cost per kWh and kWh maximum energy capacity of the considered HV battery size, respectively. Multiplying battery expenditure by 2 represents one HV battery replacement over the vehicle lifetime.

$$pOPEX = C_{Fuel}\, D_{life}\, \frac{L_{fequi}}{D_{cyc}} \tag{9}$$

Lifetime operating cost from fuel consumption $pOPEX$ is calculated from fuel cost per litre C_{Fuel}, expected lifetime mileage of the vehicle D_{life} and litres of equivalent fuel consumed over the mission profile L_{fequi}. Here, D_{cyc} represents the distance travelled on the mission profile used to calculate fuel consumption per km. Expenditure from vehicle maintenance, running, taxes and recycling at the end of life has been ignored in this activity.

Table 6. Production and fuel cost assumptions for total cost of ownership (TCO) calculations.

Parameter Cost	Value
ICE production (EUR/kW)	90 [17]
HV battery production (EUR/kWh)	200 [52,55]
eDrive production (EUR/kW)	150 [16]
Generator production (EUR/kW)	150 [16]
Diesel production (EUR/L)	1.54 [56–58]
HVO production (EUR/L)	1.81 [56,57]

3.3.4. Carbon Footprint and Total Cost Balanced Minimisation ($pCO_2 - pTCO$)

A combined minimisation objective p_{bal} comprising both powertrain lifetime carbon footprint $pCO_{2_{tot}}$ and total costs $pTCO$ is further constructed to explore the optimal sizing compromise when balancing the combined reduction of these two aspects [13]. The aim here is to analyse the corresponding lifetime expenditure in reducing the environmental impact of the two fuel cases.

$$\begin{gathered} p_{bal} = w_{CO_2}\, \frac{pCO_{2_{tot}}}{pCO_{2_{bas}}} + w_{TCO}\, \frac{pTCO}{pTCO_{bas}} \\ w_{CO_2} = 1 - w_{TCO} \end{gathered} \tag{10}$$

Here, $pCO_{2_{bas}}$ and $pTCO_{bas}$ are the carbon footprint and overall lifetime cost for the baseline sizing configuration, whereas w_{CO_2} and w_{TCO} are the weighting factors deciding the importance of environmental carbon footprint and lifetime costs in the sizing iterations, respectively.

3.4. Modelling Approach

Considering the large number of simulation iterations needed for this optimal powertrain sizing activity using particle swarm optimisation (PSO) and the long duration of the interurban mission profile, a quasi-static backward modelling approach has been selected for the actual task of sizing optimisation over the detailed forward model as previously seen in [7,15,19,59], which is supported by detailed simulation inputs from a distance based dynamic/data-driven forward model. This exhaustive model provides mission profile-specific vehicle speed (time-based), road gradient and auxiliary load consumption inputs (depending on the ambient conditions) to the quasi-static backward model for component sizing optimisation (Figure 3). The solutions of this sizing activity have been further tested using this distance-based model to assure vehicle key performance requirements, battery SoC sustaining and smooth operation on VECTO mission profiles.

3.4.1. Vehicle Resistances, Wheels and Differential

Time-based vehicle speed profile and road gradient derived from the distance-based VECTO interurban cycle baseline simulation are used as inputs to calculate the vehicle tractive resistance force F_{trct} experienced by the wheels. These include aerodynamic drag, rolling resistance and force against/with road inclination and vehicle longitudinal inertia [35]. Here, ρ_a is the ambient air density, A_v is the vehicle frontal area, C_d is the aerodynamic drag coefficient, V_v is the vehicle speed, C_{rr} is the rolling resistance coefficient of the tyres, m_v is the overall vehicle mass, g is the acceleration due to gravity and θ is the road inclination angle in degrees.

$$F_{trct} = \frac{1}{2}\,\rho_a\,A_v\,C_d\,V_v^2 + C_{rr}\,m_v\,g\,cos\theta + m_v\,g\,sin\theta + m_v\frac{dV_v}{dt} \tag{11}$$

The tractive/braking torque requirement at the wheels T_{whl} is then calculated from this overall tractive force F_{trct}, wheel radius r_{whl} and rotational inertia of the wheels J_{whl}, whereas wheel speed ω_{whl} is found from vehicle longitudinal speed input V_v while neglecting the effect of wheel slip.

$$T_{whl} = r_{whl}\,F_{trct} + n_{whl}\,J_{whl}\frac{d\omega_{whl}}{dt} \tag{12}$$

$$\omega_{whl} = \frac{V_v}{r_{whl}} \tag{13}$$

The torque output of the transmission T_{trns} is calculated using differential gear reduction G_{diff}, VECTO derived differential torque drop dT_{diff} and rotational inertia considered at the output shaft J_{diff}. Transmission out speed ω_{trns} is found using differential gear reduction G_{diff} and wheel speed ω_{whl}.

$$T_{trns} = \frac{T_{whl} + dT_{diff} + J_{diff}\frac{d\omega_{whl}}{dt}}{G_{diff}} \tag{14}$$

$$\omega_{trns} = \omega_{whl}\,G_{diff} \tag{15}$$

3.4.2. Multi-Speed Transmission and eDrive

Required torque output T_{em} and speed ω_{em} of the eDrive are calculated using transmission output torque T_{trns} and speed ω_{trns}, chosen gear ratio G_{trns}, map-based transmission torque drop dT_{trns} and rotational inertia J_{trns} at the transmission output shaft [35]. The effect of varying eDrive and transmission input shaft rotational inertia load on the complete traction chain has been avoided to simplify gear shifting dynamics by considering a fixed eDrive inertia assumption added to the transmission output shaft inertia J_{trns} for all gear selections.

$$T_{em} = \frac{T_{trns} + dT_{trns} + J_{trns}\frac{d\omega_{trns}}{dt}}{G_{trns}} \tag{16}$$

$$\omega_{em} = \omega_{trns}\,G_{trns} \tag{17}$$

eDrive torque and speed, along with map-based EM-inverter electrical efficiency η_{em} (Figure 7) are then used to calculate DC-link traction power draw P_{em} for traction and regenerative braking operation.

$$\begin{aligned} P_{em} &= \frac{\omega_{em}\ T_{em}}{\eta_{em}(\omega_{em}, T_{em})} \\ P_{em} &= \omega_{em}\ T_{em}\ \eta_{em}(\omega_{em}, T_{em}) \end{aligned} \tag{18}$$

3.4.3. Hv Battery

With the absence of an HV DC/DC converter, DC current from/to the battery I_{bat} is assumed to be the cumulative of power drawn by the eDrive P_{em}, LV auxiliaries P_{aux} and power supplied by the generator P_{gen} divided by the DC bus/battery terminal voltage V_{bat}. Auxiliary power consumption P_{aux} of the electrically operated cooling system and HVAC are input from the detailed forward model (Figure 3).

$$I_{bat} = \frac{P_{em} + P_{aux} - P_{gen}}{V_{bat}} \tag{19}$$

Battery terminal voltage V_{bat} is calculated from cell terminal voltage V_{cell} and the number of cells connected in series n_s. Cell current draw I_{cell} is found from battery current draw I_{bat} and the number of cell strands connected in parallel n_p. Positive current I_{cell} represents discharging while negative represents charging of the electrochemical cell.

$$V_{bat} = V_{cell}\ n_s \tag{20}$$

$$I_{cell} = \frac{I_{bat}}{n_p} \tag{21}$$

Cell terminal voltage V_{cell} is calculated from its open circuit voltage V_{oc} and the resistive voltage drop across the cell depending on current draw I_{cell} and its static charge/discharge resistance R_0 (Figure 1) which are functions of cell SoC.

$$V_{cell} = V_{oc}(SoC) - I_{cell}\ R_0(SoC) \tag{22}$$

Instantaneous cell/battery state of charge $SoC(t)$ is the ratio of the maximum cell charge capacity C_{max} and instantaneous charge $C(t)$, which in turn depends on the initial cell charge capacity C_{ini} and the integral of cell current drawn during the mission profile I_{cell} [35].

$$\begin{aligned} C(t) &= C(0) - \int_0^t I_{cell}\ dt \\ SoC(t) &= \frac{C(t)}{C_{max}} \end{aligned} \tag{23}$$

3.4.4. Generator and ICE

Generator charging power to the DC bus P_{gen} is considered to be ideally tracked and delivered by the ICE−generator range extender as commanded by the A-ECMS energy management strategy (Figure 6). The optimal ICE—generator combined power line shown in Figure 4B is assumed to be ideally followed by the range extender with corresponding optimal torque To_{ice} and speed ωo_{ice}. Losses in speed regulation and ICE cranking start-up, shut-down and other dynamic events are accounted for by a 3% penalty in generated power, as has been found in the distance-based forward model and literature review [60,61]. Since the ICE and generator apply the same torque and speed under steady-state operation, conversion efficiencies of both components η_{ice}, η_{gen} (Figure 4) are directly used to calculate the power injected in the form of fuel P_{fuel}.

$$P_{fuel} = \frac{P_{gen}}{\eta_{gen}(\omega o_{ice}, To_{ice})\ \eta_{ice}(\omega o_{ice}, To_{ice})}\ 1.03 \tag{24}$$

$$\begin{aligned} \omega o_{ice} &= f(P_{gen}) \\ To_{ice} &= f(P_{gen}) \end{aligned} \tag{25}$$

Cumulative fuel power P_{fuel}, lower heat value (LHV) and density of the fuel ρ_f are then used to calculate the volumetric fuel consumption L_f over a given mission profile (Table 3).

$$L_f = \frac{P_{fuel}}{LHV\ \rho_f} \tag{26}$$

Volumetric fuel consumption over the mission profile L_f is used in Section 3.3.1 along with the deviation between initial and final battery SoC to calculate the SoC equivalent fuel consumption, which is then used to compare the different size solutions in the optimisation.

4. Results and Discussion

4.1. Comparison of Baseline Vehicle Running on Diesel and HVO

From simulation results of the baseline series hybrid coach powertrain running on the VECTO interurban cycle, it can be seen that the HVO-fuelled vehicle consumes 2.86% more fuel volume and costs 12.64% higher lifetime $pTCO$ (from increased fuel consumption and price) while emitting 62.46% lower lifetime CO_2 emissions (Figures 8 and 9).

Results\Objectives	Baseline diesel	Fuel consumption minimization	CO2 minimization	TCO minimization	pCO2 - pTCO combined
Equivalent fuel consumption [L/100 km]	38.40	37.82	37.97	38.68	38.35
	-	1.50 %	1.12 %	-0.74 %	0.12 %
pCO2 [gCO2equi/km]	1137.63	1123.06	1104.30	1121.98	1112.91
	-	1.28 %	2.93 %	1.38 %	2.17 %
pTCO [euro/km]	0.791	0.823	0.763	0.720	0.721
	-	-4.06 %	3.43 %	8.88 %	8.80 %
ICE-GEN size [kW]	160.0	186.3	178.9	120.0	120.0
HV Battery size [kWh]	240.0	240.0	162.5	162.5	162.5
eDrive size [kW]	240.0	342.2	336.9	240.0	257.7
Gear ratio 1 [-]	17.269	13.066	13.156	17.269	16.093
Gear ratio 2 [-]	9.004	7.226	7.246	9.004	8.349
Gear ratio 3 [-]	5.055	4.443	4.446	5.055	4.942

Figure 8. Quantitative comparison of diesel−fueled powertrain size solutions running on VECTO interurban cycle focused on minimisation of fuel consumption, carbon footprint (pCO_2), lifetime costs ($pTCO$) and environmental-economic balanced objective ($pCO_2 - pTCO$) against the baseline case. The corresponding choice of optimised powertrain dimensions have also been listed.

Results\Objectives	Baseline HVO	Fuel consumption minimization	CO2 minimization	TCO minimization	pCO2 - pTCO combined
Equivalent fuel consumption [L/100 km]	39.50	38.92	39.11	39.80	39.39
	-	1.45 %	0.97 %	-0.76 %	0.28 %
pCO2 [gCO2equi/km]	427.07	424.64	401.66	406.20	402.71
	-	0.57 %	5.95 %	4.89 %	5.7 %
pTCO [euro/km]	0.891	0.945	0.852	0.821	0.822
	-	-6.04 %	4.41 %	7.86 %	7.75 %
ICE-GEN size [kW]	160.0	240.0	156.4	120.0	120.0
HV Battery size [kWh]	240.0	240.0	162.5	162.5	162.5
eDrive size [kW]	240.0	340.2	329.1	240.0	260.2
Gear ratio 1 [-]	17.269	13.006	14.437	17.269	15.951
Gear ratio 2 [-]	9.004	7.227	8.342	9.004	8.358
Gear ratio 3 [-]	5.055	4.440	4.908	5.055	4.946

Figure 9. Quantitative comparison of HVO−fueled powertrain size solutions running on VECTO interurban cycle focused on minimisation of fuel consumption, carbon footprint (pCO_2), lifetime costs ($pTCO$) and environmental-economic balanced objective ($pCO_2 - pTCO$) against the baseline case. The corresponding choice of optimised powertrain dimensions have also been listed.

4.2. Optimal Powertrain Sizing for Fuel Consumption Minimisation

The series-HEV fuel economy-focused sizing solution shows a reduction in carbon footprint over the baseline configuration (1.28% for diesel and slightly lower 0.57% CO_2 reduction for HVO) due to decreased fuel usage but led to augmented lifetime costs from an expense no bound component sizing approach (Figures 8–10). When comparing fuel economy-based solutions of diesel and HVO against their baseline cases, it is clear that HVO takes a larger penalty in $pTCO$ than diesel (−6.04% against −4.06%) for a similar lowering of fuel consumption (1.45 and 1.5% respectively). The effect of powertrain efficiency improvement on pCO_2 reductions is also much lesser for HVO due to inherently low fuel carbon footprint while the penalty on the corresponding $pTCO$ is far larger than in diesel as a result of greater price and chosen larger optimal range extender component size (Figures 8 and 9 and Table 6). Fuel economy-sized solutions solely focused on improving efficiency also present a barely restricted choice of eDrive sizing, thus profiting from the possibility of gear ratio tuning due to the corresponding relaxation on dependent gear ratio search space in Table 4 (satisfying maximum wheel torque requirements in Table 1). The maximum possible HV battery size is chosen in this case as the approach considers increment in overall charge capacity (Ah) through added cell strands in parallel, which also leads to a drop in overall resistance and corresponding battery level losses.

From Figure 10, it becomes clear that the baseline and fuel economy-focused sizing configurations will not be the best-suited solutions for minimising environmental impact or improving the economic feasibility of the current plug-in series-HEV coach use case running on the interurban mission profile with a lifetime mileage of 550,000 km.

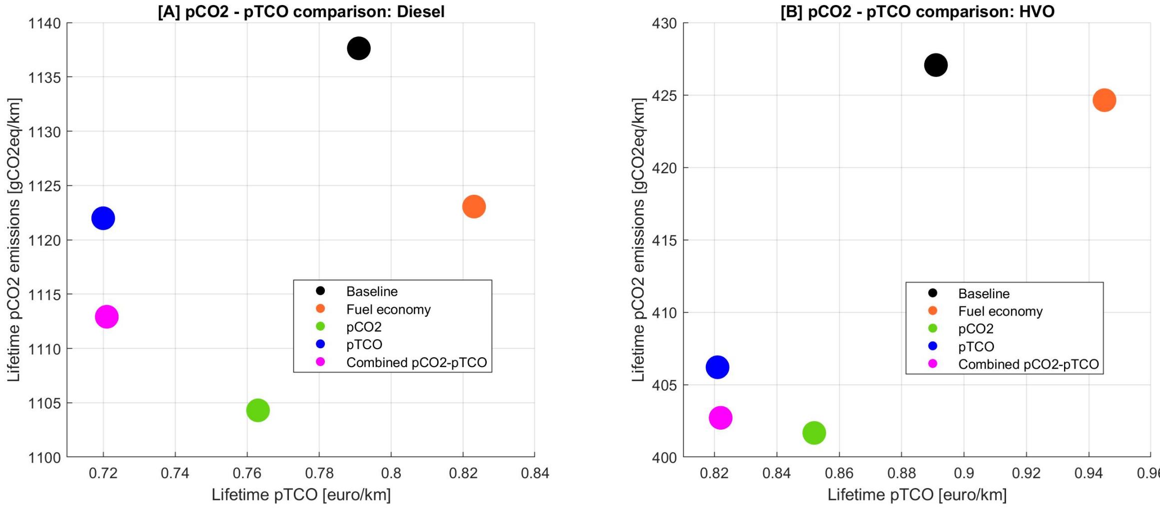

Figure 10. Comparison of lifetime powertrain cost ($pTCO$) and carbon footprint (pCO_2) reductions for various series-HEV optimal sizing configurations including baseline, fuel economy, pCO_2 minimisation, $pTCO$ minimisation and $pCO_2 - pTCO$ combined minimisation solutions for (**A**) diesel and (**B**) HVO-fuelled cases.

4.3. Optimal Powertrain Sizing for Carbon Footprint Minimisation (pCO2)

When lifetime emissions (pCO_2) is the minimisation objective, the methodology tries to find a pure carbon footprint reduction-based compromise between decreasing production and vehicle running impact. This global approach already shows improvement over the above-discussed baseline and fuel economy-focused solutions in reducing not only carbon footprint but also lifetime costs for diesel (2.93% and 3.43%) and HVO (5.95% and 4.4%) cases (Figures 8–10). When comparing pCO_2 reduction solutions for both fuels, minimal battery size is selected, demonstrating the small effect of battery sizing on overall powertrain efficiency improvement and rather a dominant impact from its production emissions (for the current ZUEZ-oriented battery size search space). A slightly smaller but free size is still selected for the ICE range extender (between upper and lower size bounds), demonstrating a balancing act between powertrain production and WTW emissions reduction. eDrive as a component, along with the above-discussed possibility of gear ratio tuning on large size selection, shows the highest potential in reducing lifetime carbon footprint through traction chain efficiency and regenerative braking improvements at the expense of added production emissions when compared to the other components. While focusing on pCO_2 reduction, better control over $pTCO$ values for HVO than for diesel (4.41% against 3.43%) with lesser improvement in fuel consumption (0.97% against 1.12%) indicates a higher inclination of production aspects in carbon footprint reduction for HVO case than the diesel application, which is obvious from the renewable nature of the fuel.

4.4. Optimal Powertrain Sizing for Lifetime Cost Minimisation (pTCO)

If the optimisation objective is shifted to lifetime costs reduction, improvement in $pTCO$ is found at the expense of a much higher carbon footprint, unlike for pCO_2 minimisation-focused solutions, meaning pursuing pCO_2 lowering generated more balanced savings in both carbon footprint and lifetime costs when compared with $pTCO$ minimisation-focused sizing (Figures 8–10). $pTCO$-based size for HVO could keep better control over carbon footprint compared to the diesel fuelling case (4.89% against 1.38% reduction in pCO_2) due to the low carbon nature of HVO while generating high reductions in overall cost (7.86% and 8.88% respectively). In the $pTCO$ minimisation case, the algorithm chose the smallest possible size of all components, showing the dominant impact of production costs over running costs for the given combination of plug-in series-HEV

ZUEZ coach use case, VECTO interurban cycle and a lifetime mileage of 550,000 km while running on both diesel as well as HVO fuels.

4.5. Environmental–Economic Balanced Optimal Sizing ($pCO_2 - pTCO$)

With the aim to further understand the compromise between minimising carbon footprint and lifetime powertrain costs, a combined objective with equal weighting on baseline normalized reductions in pCO_2 and $pTCO$ is considered (Equations (9) and (10)) [13]. The methodology tries to find a compromise between lowering the two objectives while aiming for the least possible combined normalised solution p_{bal}, which is slightly inclined towards reduction of $pTCO$ over pCO_2 in this case and generates outcomes balanced between those from the carbon footprint and total cost minimisation-focused cases (Figures 8–10). It is to be noted that this balanced sizing solution has higher fuel consumption than the fuel economy and pCO_2 cases, further proving the greater impact of production aspects in minimising balanced lifetime $pTCO$ and pCO_2 when compared to vehicle running effects for the current use case and given assumptions. For the combined $pCO_2 - pTCO$ minimisation objective, the algorithm chooses the minimum possible sizing of the range extender and HV battery along with balanced dimensioning of eDrive size which, also facilitates the possibility of gear ratio tuning (Figures 8 and 9). This further demonstrates the higher capability and importance of the eDrive sizing in controlling running aspects at the expense of production impact compared to other powertrain subsystems.

4.6. Comparison of Powertrain Operation

Range extender, battery power and SoC trajectory comparison for baseline, fuel economy, carbon footprint, the total cost of ownership and balanced environmental-economic ($pCO_2 - pTCO$)-focused sizing solutions running on VECTO interurban cycle (Figure 2) have been shown in Figure 11 for diesel and Figure 12 for HVO cases, respectively.

Depending on the chosen size of the range extender, the ECMS control strategy is scaled accordingly (Figure 6) and the inner optimisation loop tunes the fixed value battery equivalent costate (λ) to achieve end cycle SoC sustenance to an acceptable level (Figures 11 and 12). Effects of this fixed calibration can be seen in the electrical power output of the range extender and the HV battery. When comparing baseline, fuel economy-focused and pCO_2-focused sizing solutions (black, blue, red), greater energy recuperation during regenerative braking is evident from higher battery charging power (negative power) for the latter two cases as a result of larger eDrive size (Figures 8 and 9).

Range extender power output is related to the chosen component size for all optimisation cases. When a large range extender is selected, lesser power is drawn from the HV battery and vice versa. With such a design solution (fuel economy case−blue), this subsystem may also be run inefficiently at lower power demands (3750 s–4500 s) following the SoC sustenance and ECMS commands (Figure 12). Running the range extender inefficiently with varying power draw also occurs for sustaining the battery SoC inside a permissible window (Figure 6), which is evident in the pCO_2-focused case where the smaller battery size leads to a greater deviation of SoC from its initial value and a pronounced effect of equivalence factor adaption coefficient (k_c) on the range extender power output (Figures 11 and 12).

For the $pTCO$ and balanced $pCO_2 - pTCO$-focused solutions of the diesel and HVO fuelled cases, the power flow is closely matched as the same minimal sizes of range extender and HV battery are chosen for both cases. Slightly higher SoC levels of the $pTCO$-focused case throughout the cycle suggest slightly less eDrive power consumption and a bit more range extender power than for the $pCO_2 - pTCO$ combined case. However, greater energy recuperation in regenerative braking for the combined case which is evident from the slightly higher charging power of the battery (negative power) helps to equal SoC during the cycle, sustain at the end of the cycle and also leads to an overall better fuel economy over the $pTCO$-focused case (dimensions given in Figures 8 and 9).

Concerning battery SoC trajectories, when the minimal size of the range extender and HV battery is selected ($pTCO$ and combined minimisation cases), a greater deviation from the initial SoC value during the drive cycle is evident for both fuel cases. As we compare the increasing range extender and battery size from other powertrain design solutions, the SoC deviations from its initial value during the drive cycle are much less (baseline, pCO_2 followed by fuel consumption minimisation case). A larger size will lead to lower levels of intrusion from the in-cycle SoC sustenance mechanism (k_c) on the ECMS strategy, which further adds to the high-efficiency operation of the powertrain seen through corresponding better fuel economy results (Figures 8 and 9). The exceptional case of HVO fuel economy-based powertrain design comes from a comparatively larger selection of range extender size, which the ECMS does not let operate at lower loads, leading to higher variations in battery SoC and k_c, changing the behaviour of the complete powertrain (Figure 12).

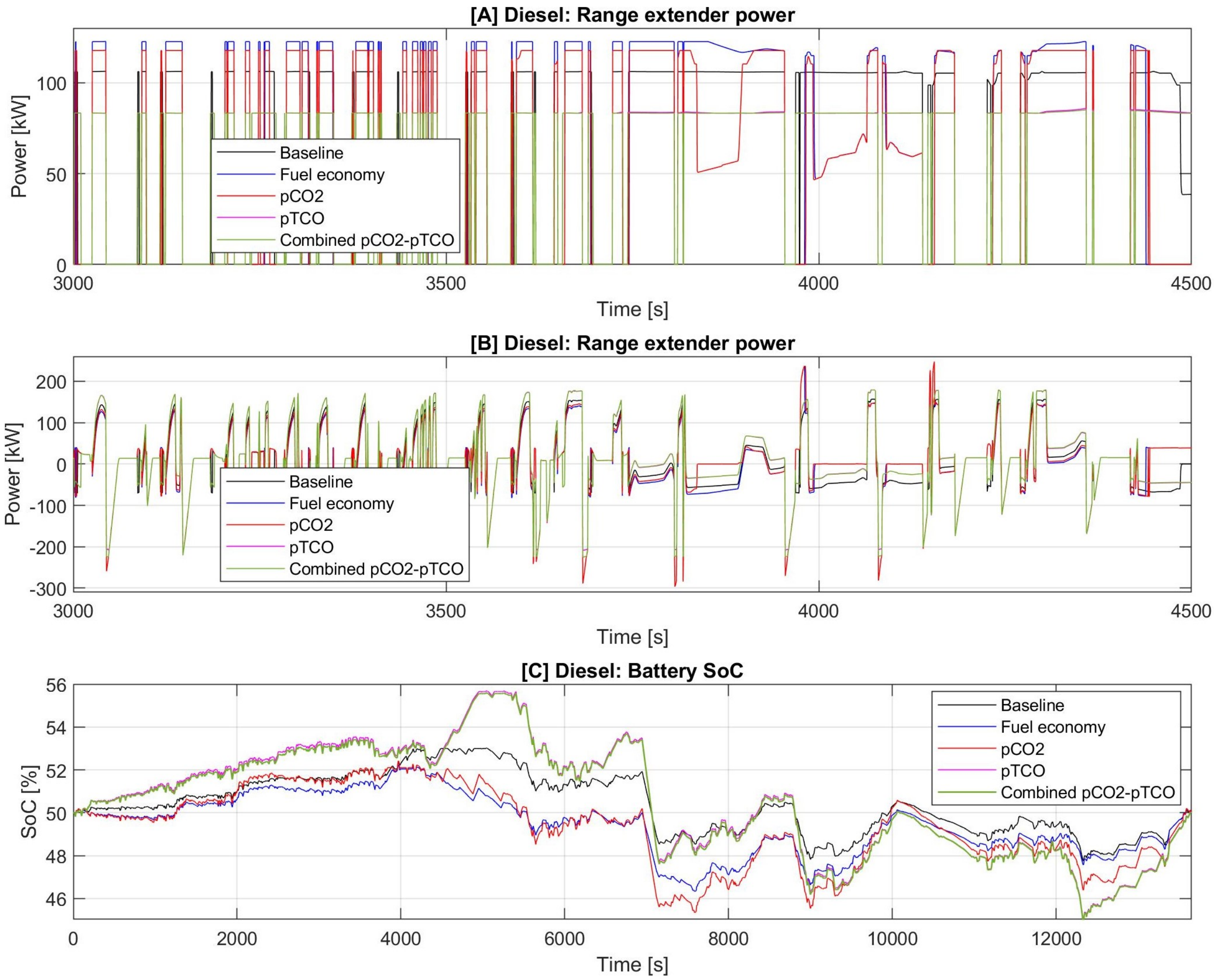

Figure 11. Comparison of (**A**) range extender power output, (**B**) battery power draw and (**C**) SoC variation for various diesel fueled sizing solutions. Range extender, battery and eDrive size varied for different solutions as seen in Section 4.

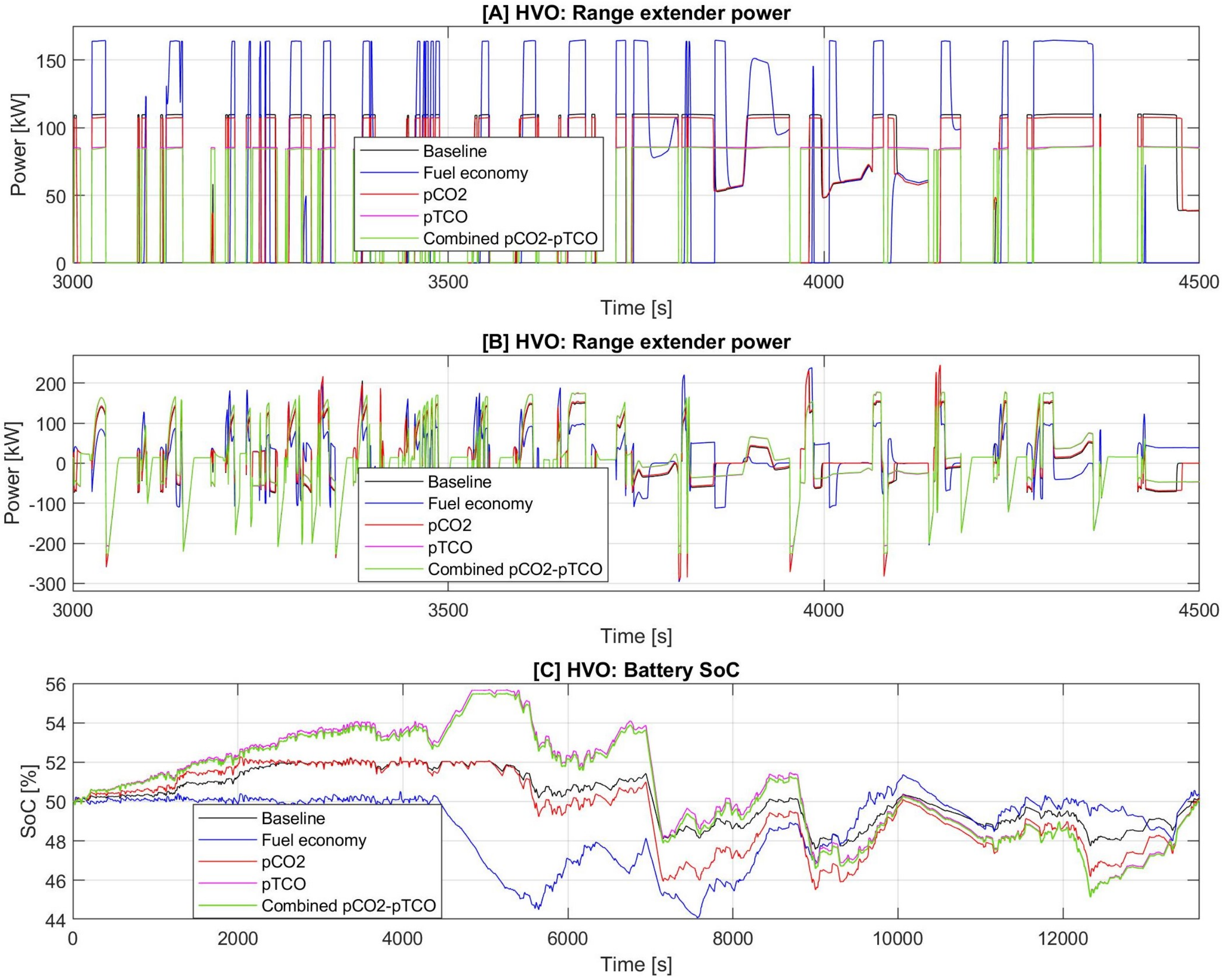

Figure 12. Comparison of (**A**) range extender power output, (**B**) battery power draw and (**C**) SoC variation for various HVO-fueled sizing solutions. Range extender, battery and eDrive size varied for different solutions as seen in Figure 9.

4.7. Comparison of eDrive Operation

eDrive operating points for baseline and fuel economy-focused diesel-fueled sizing solutions running on VECTO interurban cycle have been shown in Figure 13 to compare the operation of the smallest (most constrained) and largest (least constrained) traction chain designs (dimensions in Figure 8).

At the component level, eDrive sizing has been found to be a compromise between improving the scope of regenerative braking and bringing the operating points (during traction and braking) towards the higher efficiency zone while respecting the interdependent design constraints for eDrive and gear ratios (seen in Figure 7, Table 4). eDrive sizing shifts the torque capacity and, thus, the operating points relative to the efficiency map vertically. On the other hand, gear ratios can move the operating point placement with respect to both eDrive torque and speed (vertically and horizontally as seen in Figure 13). With the sole aim of improving operating efficiency for the fuel economy-focused solution, the operating points can be seen to shift up and towards higher efficiency zone of eDrive operation using lowered gear ratios (refer Figure 7 for efficiency map, Table 4 for dimensions). Although still limited, the scope of regenerative braking has also been improved with a larger eDrive size for the fuel economy-focused solution (Figure 13). Torque output from the eDrive is higher when lowered gear ratios are selected to deliver the same traction wheel torque. Armature friction torque loss is also proportionally increased for a larger eDrive size.

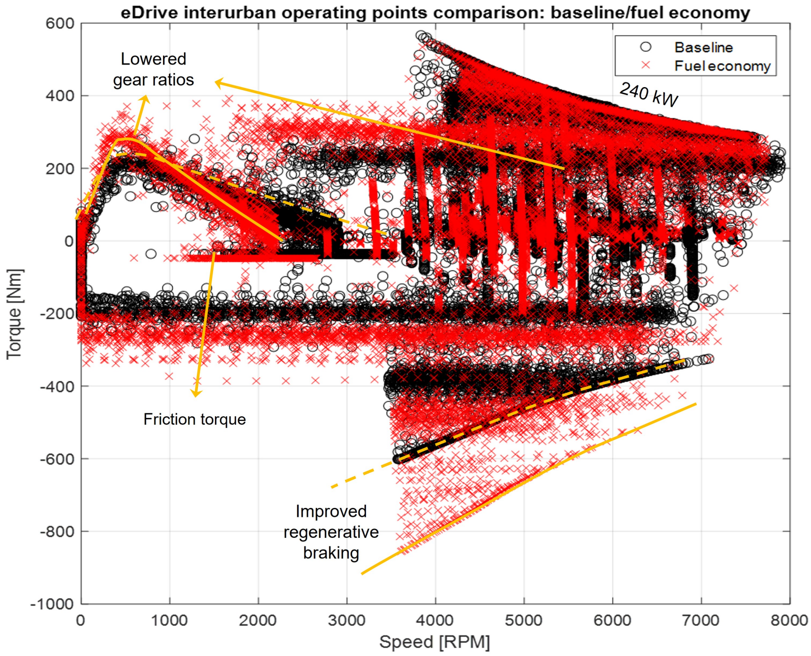

Figure 13. Comparison of eDrive operating points for the smallest and largest sizing solutions (baseline and fuel economy-focused). Shift along torque axis (vertical) can be linked to eDrive sizing as well as gear ratio optimisation, whereas shift along speed axis (horizontal) is related to only gear ratio optimisation whose constraints are relaxed for larger eDrive sizing.

5. Conclusions

The main objective of this work was to calculate, analyse and compare the optimal powertrain sizing of a plug-in series hybrid coach with a 100 km zero urban emission zone (ZUEZ) range running on conventional diesel or alternative hydrotreated vegetable oil (HVO) aimed at minimising lifetime environmental impact and total cost of ownership (TCO). Optimal sizing was done using a nested co-design methodology with the outer component sizing loop using particle swarm optimisation (PSO), whereas the inner HEV control loop employed adaptive ECMS for energy management and local minimisation for gear selection to reduce energy consumption. First, powertrain sizing optimisations solely focused on fuel economy, carbon footprint or lifetime cost minimisation were calculated to understand and compare how they achieved their primary objective and how their pursuit affected other important design outcomes. Optimal dimensioning aimed at finding a balanced compromise between reduction of environmental impact and overall costs was then explored for HVO and diesel-fuelled cases. Finally, the main results of all powertrain sizing optimisation solutions were compared to assess their impact on fuel economy, lifetime carbon footprint and TCO, to recognise the most suitable design approach for such unconventional electrified powertrains, especially when integrated with alternative fuels.

- For a baseline powertrain manually sized to satisfy vehicle key performance requirements and set rules (ZUEZ range), HVO fuel offered a 62.46% reduction in lifetime carbon footprint at the expense of 12.64% higher overall expenditure over conventional diesel. Integration of alternative HVO can thus significantly lower carbon footprint at the expense of some lifetime costs, which could be balanced by government incentives.
- When aiming for fuel efficiency, optimal sizing for diesel and HVO cases gave 1.5% and 1.45% consumption reductions over baseline but with marginal lowering of CO_2 emissions (1.28% and 0.57%) at the expense of highly elevated total costs (4.06% and 6.04%) from the production of larger components. This indicates that the conventional approach to powertrain sizing aimed at efficiency improvement may not be the best solution from an environmental or even an economic point of view, especially for

new upcoming electrified powertrains such as the current unconventional plug-in series-HEV coach running on alternative HVO.

- With lifetime cost as the minimisation objective, TCO reductions of 8.88% and 7.86% over baseline were achieved for diesel and HVO with some improvement on carbon footprint (1.38% and 4.89%) even after consuming more fuel (0.74% and 0.76%), showing considerable dependency of the overall environmental impact on vehicle production emissions. Due to the environmentally friendly nature of HVO, this TCO-focused sizing (highly dependent on production aspects) gave much greater benefits in CO_2 emission reduction than the diesel case, which signifies the decreasing importance of powertrain efficiency over production aspects in lowering emissions for unconventional vehicle topologies and especially for alternative fuels. Singular focus on overall carbon footprint minimisation in the case of diesel and HVO gave 2.93% and 5.95% CO_2 reductions and also generated favourable outcomes on other targets such as TCO with 3.43% and 4.41% or fuel consumption minimisation with 1.12% and 0.97% benefits, respectively.
- Finally, considering a balanced objective with equal weighting on CO_2 and TCO minimisation against the baseline, substantial benefits for diesel and HVO cases were obtained with lifetime carbon footprint reductions of 2.17% and 5.7%, and total cost reductions of 8.8% and 7.75%, respectively. For calculating the absolute minimum of this combined equally weighted objective, the considered optimisation approach slightly favoured TCO reduction over CO_2 emissions in comparison to the previous CO_2-focused sizing case, which also generated balanced results. When comparing fuel consumption reduction results with the CO_2-focused case (0.12% against 1.12% for diesel and 0.28% against 0.97% for HVO), the importance of production aspects over powertrain efficiency in balanced minimisation of both lifetime environmental impact and overall expenditure becomes further evident for the current plug-in series-HEV powertrain topology and especially HVO fuel. On comparing carbon footprint and total costs with CO_2-focused and TCO-focused solutions, it can be seen that the balanced solution offered a substantial lowering of CO_2 emissions for only a slight increase in TCO. It can be concluded that such unconventional powertrain architectures running on different fuels present a greater degree of freedom over their design optimisation, requiring application-specific and balanced design goals to achieve the best outcomes.
- Among various powertrain components for the given series-HEV coach use case, eDrive sizing has been found to give the highest CO_2 and cost–benefit through efficiency improvement against increasing production impact owing to better eDrive operation, the improved scope of regenerative braking and the added possibility of gear ratio tuning with the larger size. ICE range extender size showed less effect on overall powertrain efficiency against its corresponding production impact. At the same time, the HV battery gave the least efficiency improvement favouring the selection of the smallest battery size in case of most optimisation objectives due to its dominant production aspect.

Perspectives:

- Optimal powertrain sizing considering plug-in charging with SoC depleting mode (plug-in HEV) or ZUEZ running with electric-only operation in the urban part of the VECTO interurban cycle could also be considered in the future.
- The current optimal sizing solutions for various minimisation objectives have been generated considering urban and interurban driving scenarios (VECTO interurban cycle). Another aspect of coach vehicles involves continuous driving on highways at sustained speeds. Actual anticipated use could be further considered by combining different mission profiles or even using real-world routes.
- The effect of changing component size on vehicle mass and the corresponding variation in vehicle tractive resistance, power consumption and optimally sized powertrain solutions could be explored.

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Abbreviations

The following abbreviations are used in this manuscript:

APSO	Accelerated Particle Swarm Optimisation
A-ECMS	Adaptive Equivalent Consumption minimisation Strategy
BEV	Battery Electric Vehicle
CO_2	Carbon Dioxide
CNG	Compressed Natural Gas
CAPSO	Chaos-enhanced Accelerated Particle Swarm optimisation
ECMS	Equivalent Consumption Minimisation Strategy
EU	European Union
eDrive	Electric Drive
EM	Electric Machine
FCEV	Fuel Cell Electric Vehicle
GHG	Green House Gases
HD	Heavy-Duty
HVO	Hydrotreated Vegetable Oil
HVAC	Heat, Ventilation and Air conditioning
HEV	Hybrid Electric Vehicle
HV	High Voltage
ICE	Internal Combustion Engine
LV	Low Voltage
NOx	Nitrous Oxide
PMP	Pontryagin's Minimisation Principle
PSO	Particle Swarm Optimisation

pCO_2	Powertrain lifetime carbon dioxide emissions
$pTCO$	Powertrain Total Cost of Ownership
pCAPEX	Powertrain Capital Expenditure
pOPEX	Powertrain Operating Expenditure
S-HEV	Series Hybrid Electric Vehicle
SoC	State of Charge
TCO	Total Cost of Ownership
TTW	Tank To Wheel
VECTO	Vehicle Energy Consumption calculation TOol
WTW	Well To Wheel
WTT	Well To Tank
ZUEZ	Zero Urban Emission Zone

Appendix A. Optmised Gear Shifting Based on eDrive Loss Minimisation

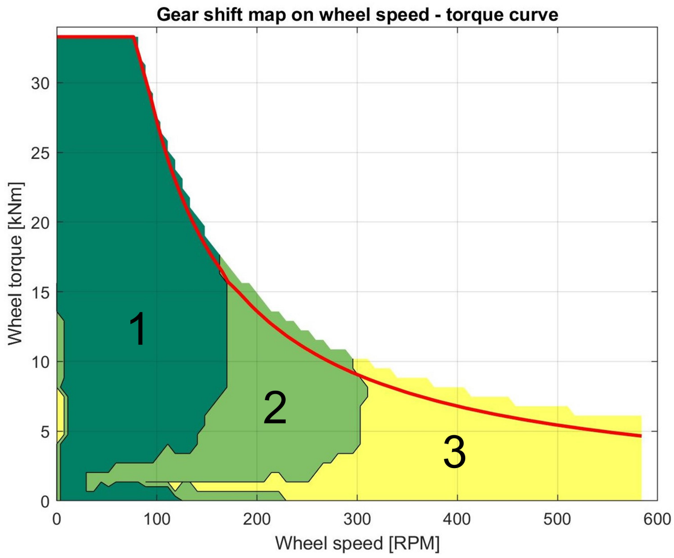

Figure A1. Optimal gear shift pattern depending on wheel speed and requested torque based on local minimisation of eDrive losses.

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