Development of a new hybrid bus for urban public transportation

Original
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Highlights

- New plug-in series hybrid electric powertrain developed for revamping old urban buses
- Assessment of its performance through experimental tests in real world operating conditions
- Impressive energy and operating costs savings vs conventional buses highlighted

Figure Captions

Figure 1: Scheme of the main hybrid powertrain components.

Figure 2: HYBUS prototype rendering.

Figure 3: HYBUS prototype production: original bus (top left); removal of the old 9.5 liter diesel engine from the rear section of the vehicle (top right); installation of the APU (bottom, left); first HYBUS prototype (bottom right).

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Figure 5: Route 18-forward: SOC profile.

Figure 6: Route 63-forward: real mission profile.

Figure 7: Route 63-forward: SOC profile.

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Figure 13. DP Optimization: Power requested to ICE.

Figure 14. DP Optimization: Operating points of the ICE on the Brake Specific Fuel Consumption (BSFC) map versus engine speed and load (shown as Brake Mean Effective Pressure, BMEP).

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Figure 16. Operating modes selected by the DP plotted on an EM speed vs requested power map.

Figure 17. Operating modes selected by the DP plotted on a vehicle acceleration vs vehicle speed map.

Figure 18. Battery SOC comparison over the complete real driving cycle.

Figure 19. Comparison of operating points of ICE on the Brake Specific Fuel Consumption (BSFC) map versus engine speed and load (shown as Brake Mean Effective Pressure, BMEP).

Figure 20. Cumulative fuel consumption comparison over the complete driving cycle.

Figure1

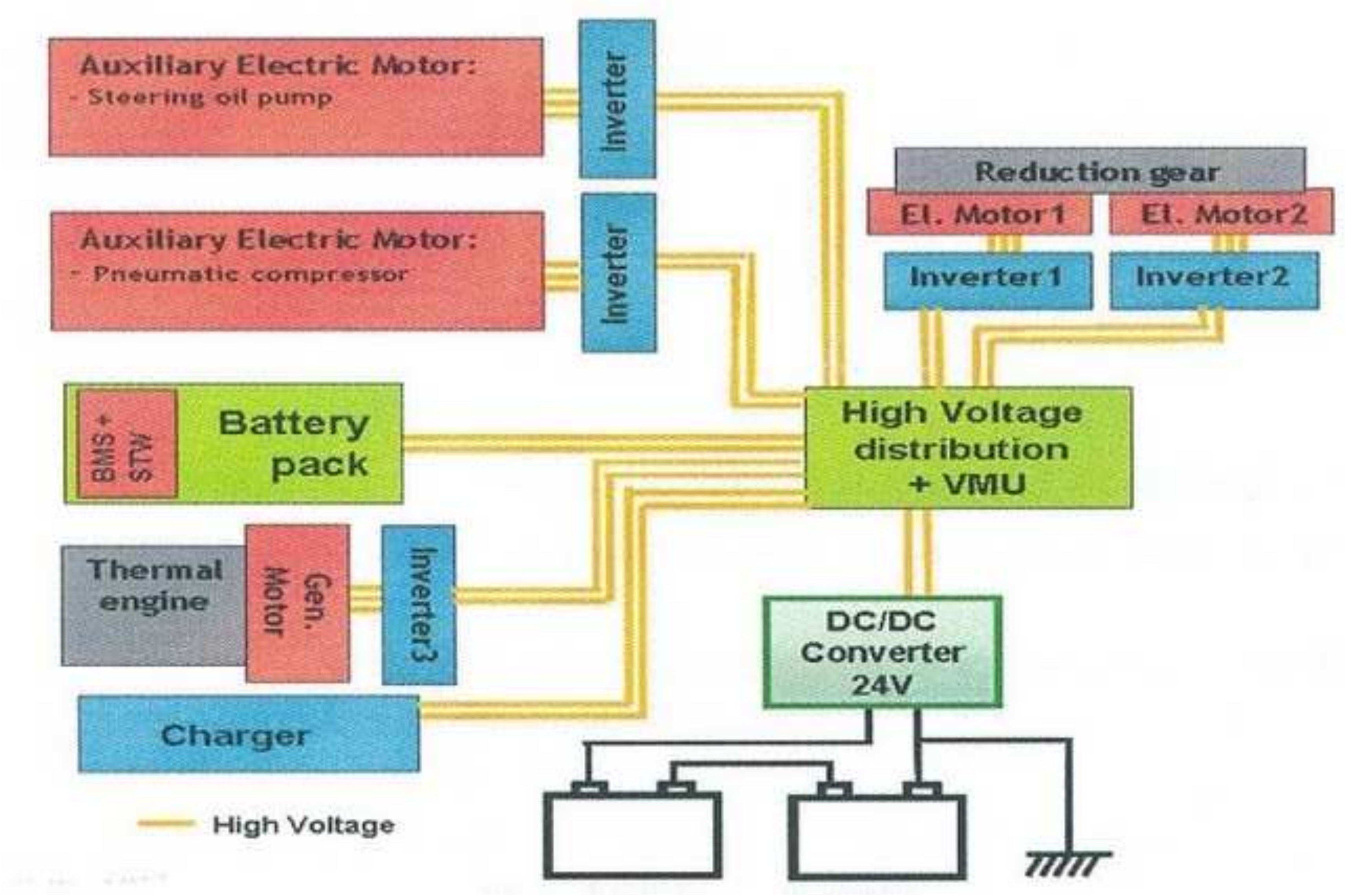
Auxiliary Electric Motor:
- Steering oil pump
Inverter
Auxiliary Electric Motor:
- Pneumatic compressor
Inverter
Reduction gear
El. Motor1
El. Motor2
Inverter1
Inverter2
BMS + STW
Battery pack
High Voltage distribution + VMU
Thermal engine
Gen. Motor
Inverter3
DC/DC Converter 24V
Charger
High Voltage

Figure2

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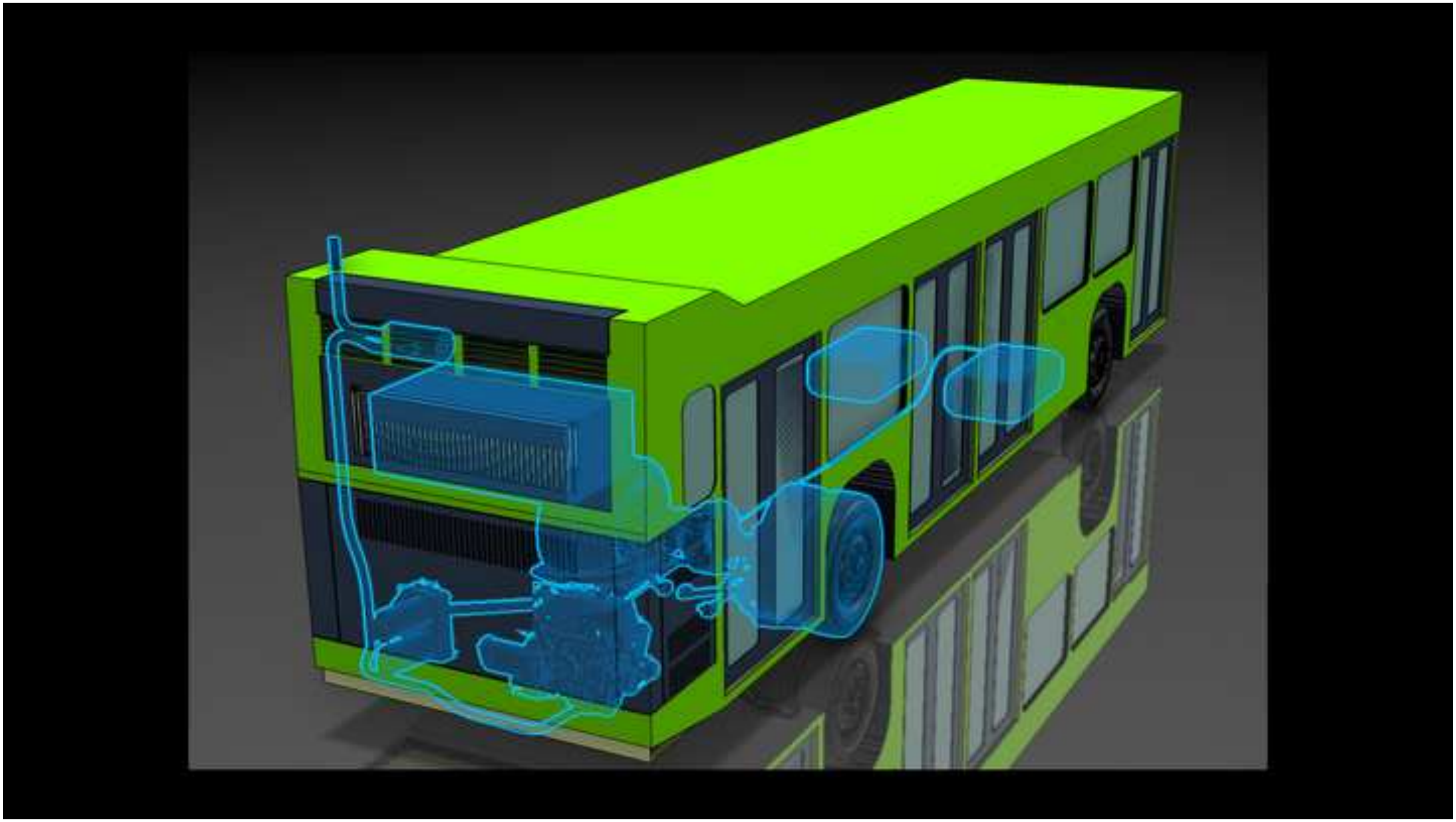

Figure3

Figure4

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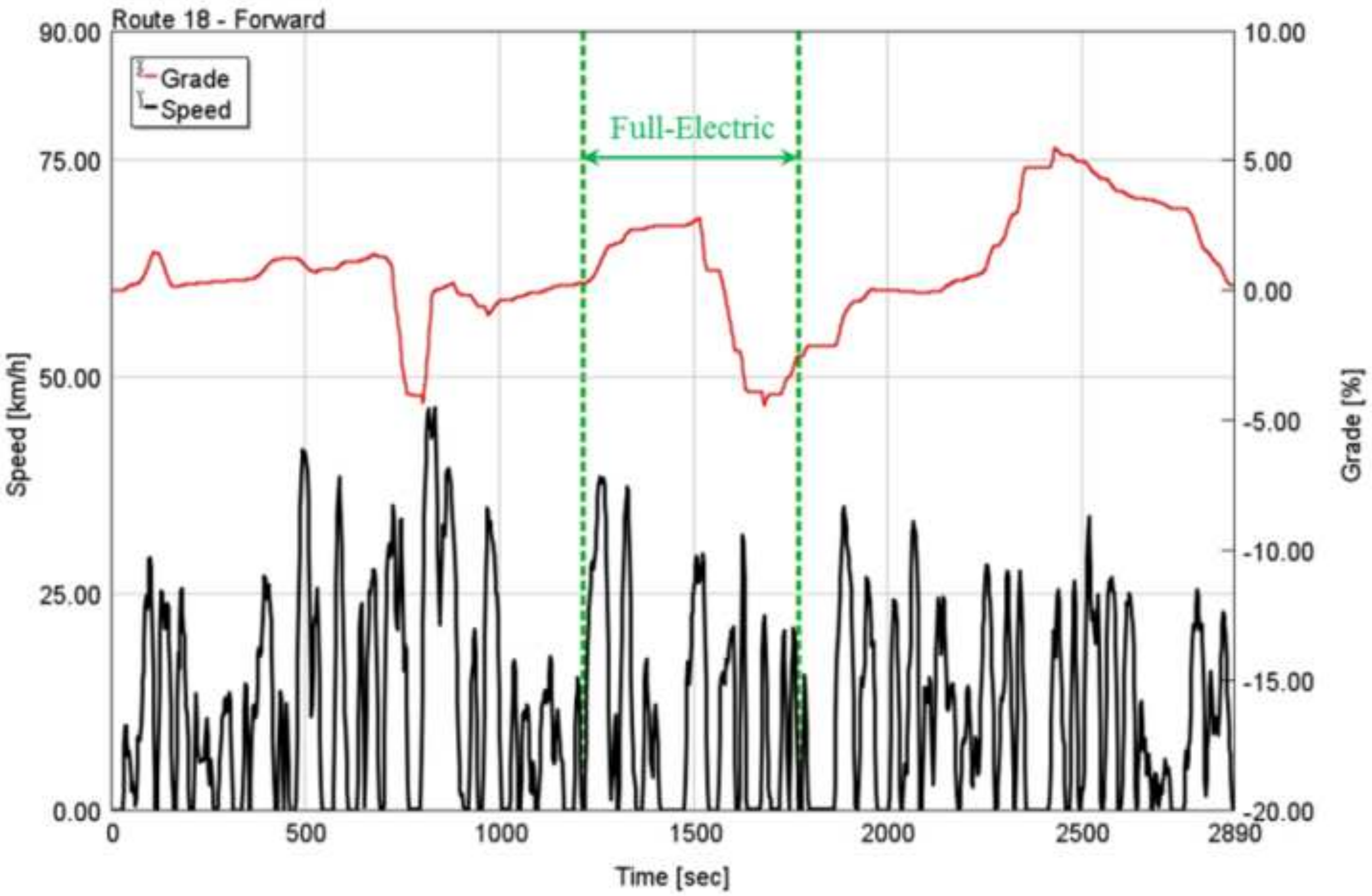

Figure5

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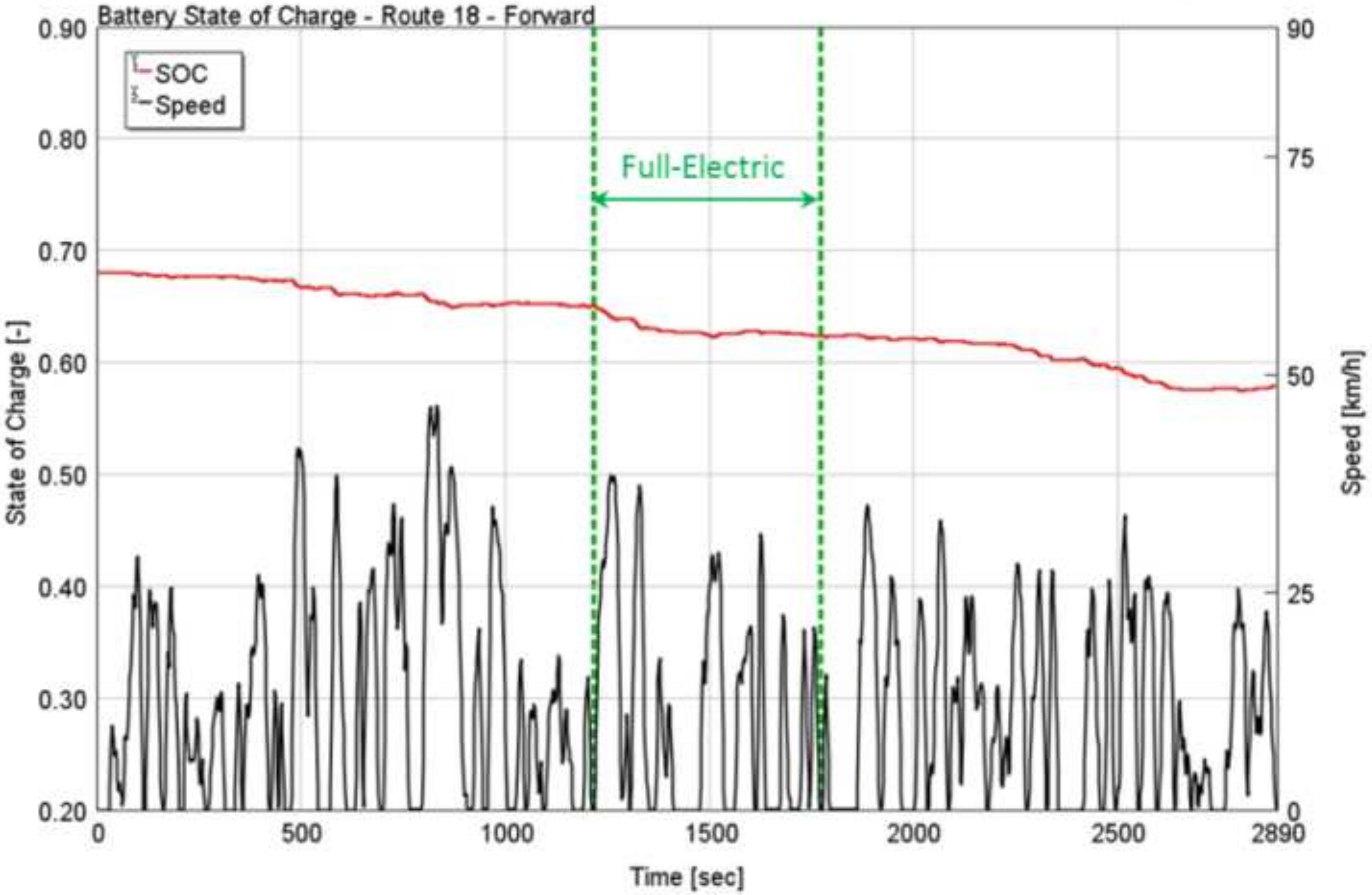

Figure6

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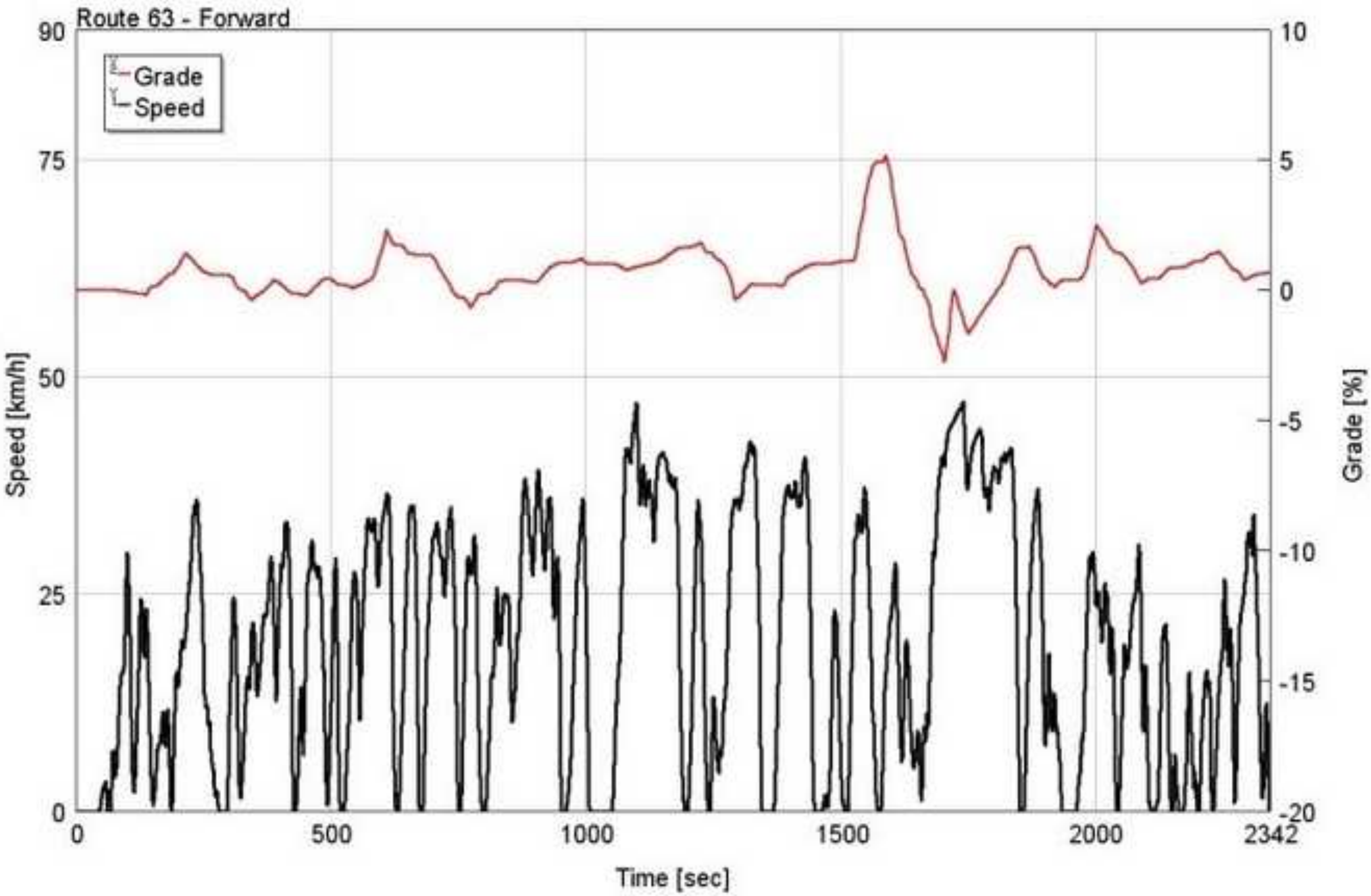

Figure7

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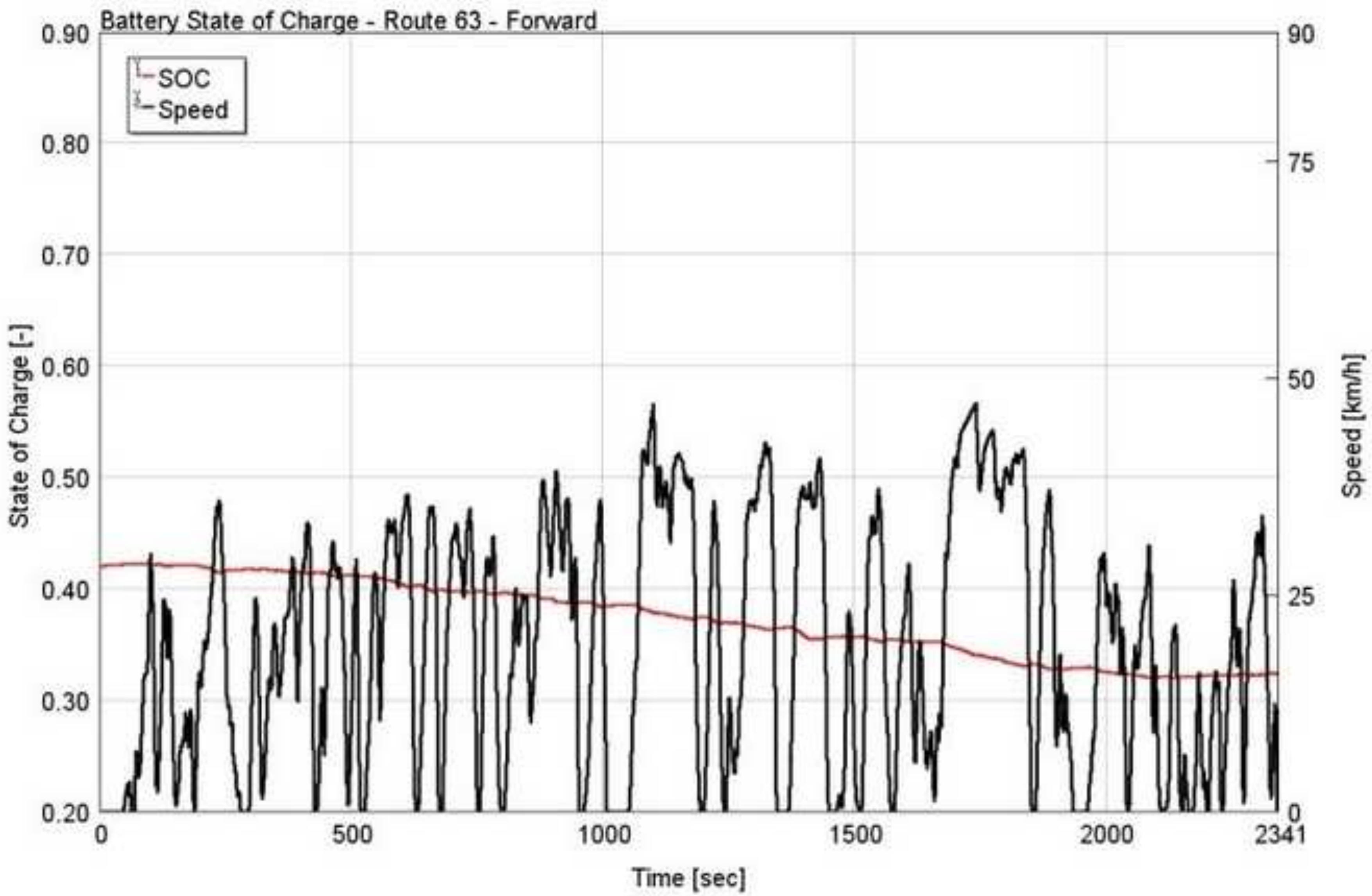

Figure8

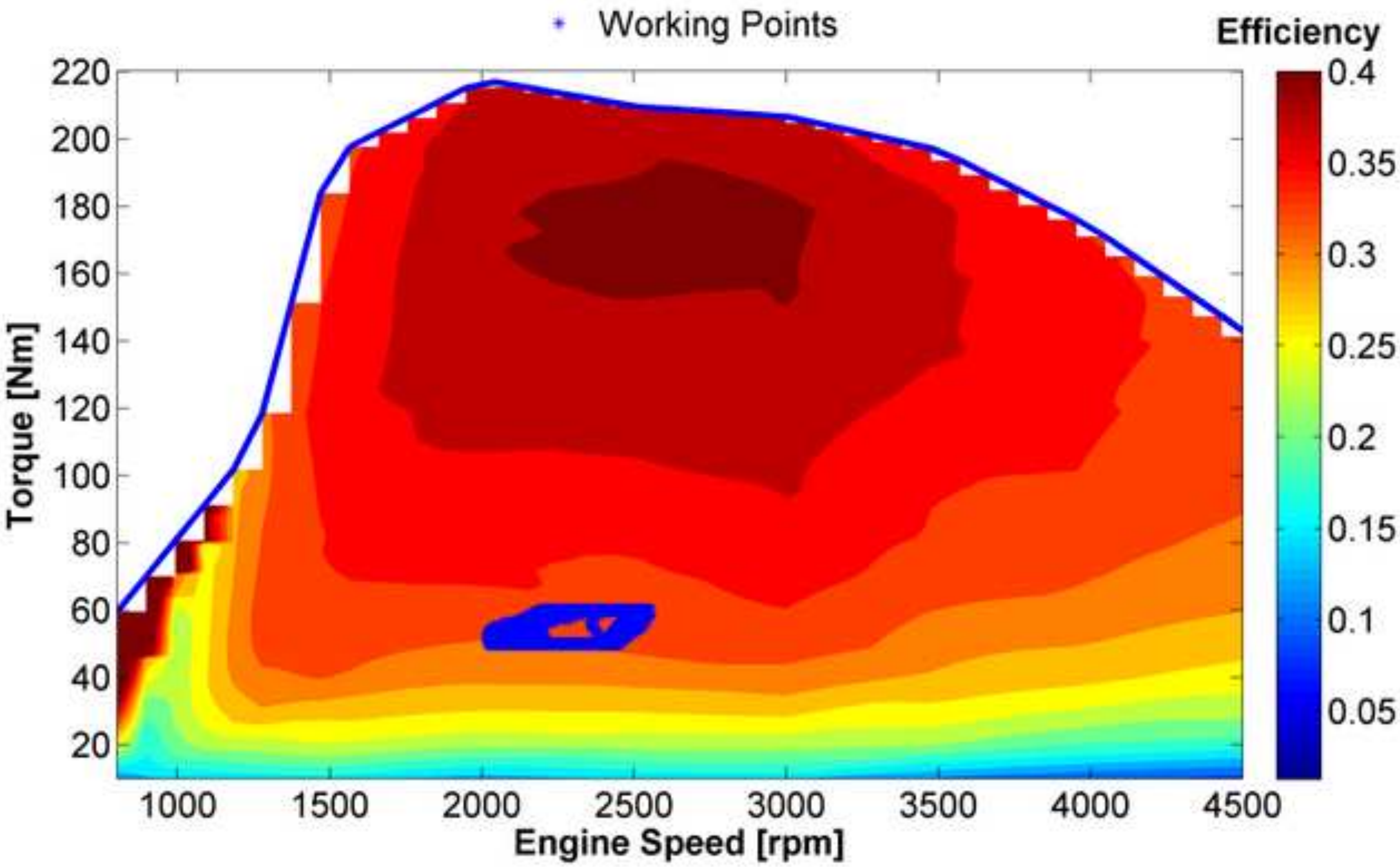
* Working Points
Efficiency
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Torque [Nm]
220
200
180
160
140
120
100
80
60
40
20
Engine Speed [rpm]
1000
1500
2000
2500
3000
3500
4000
4500

Figure9

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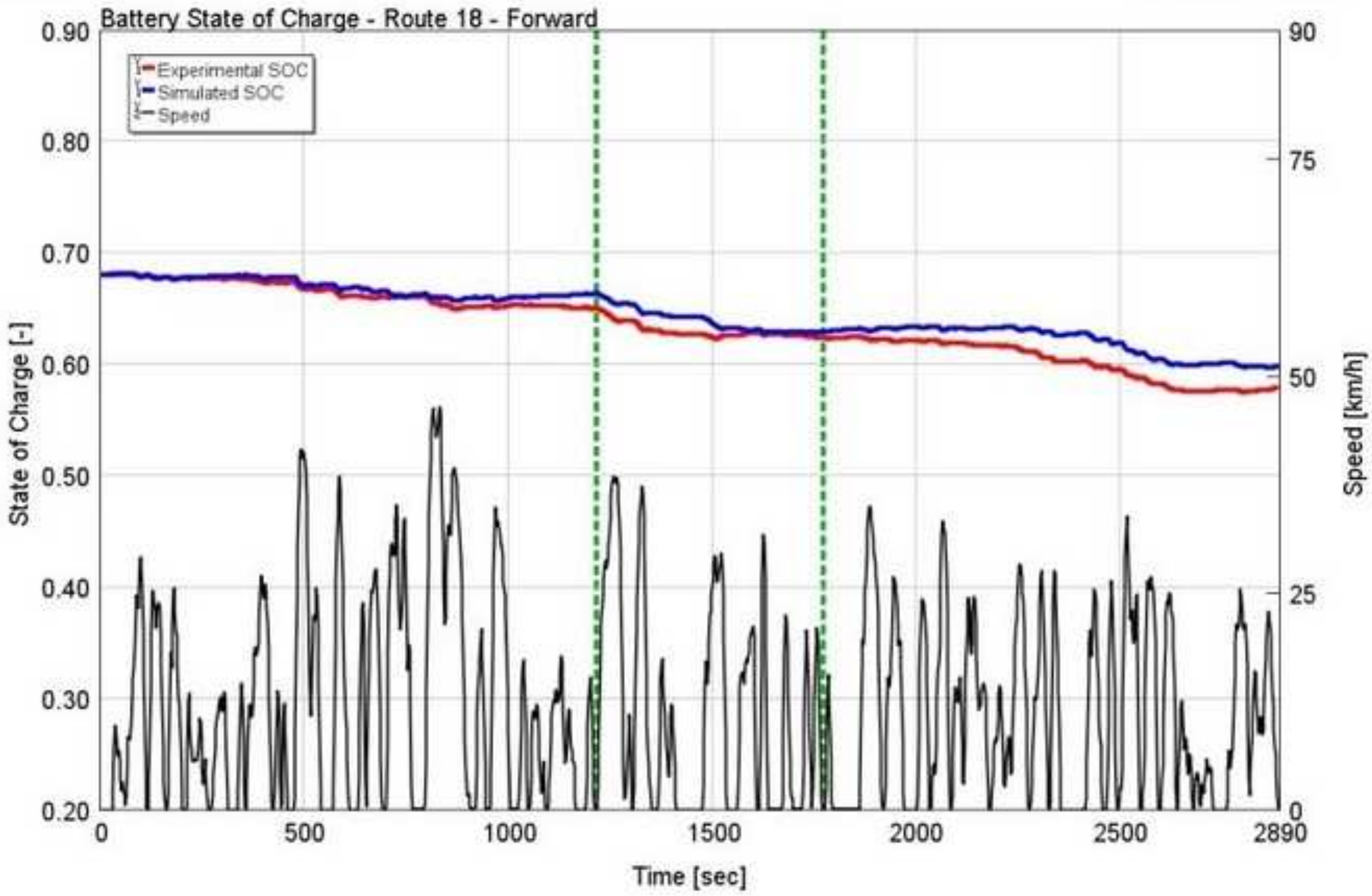

Figure10

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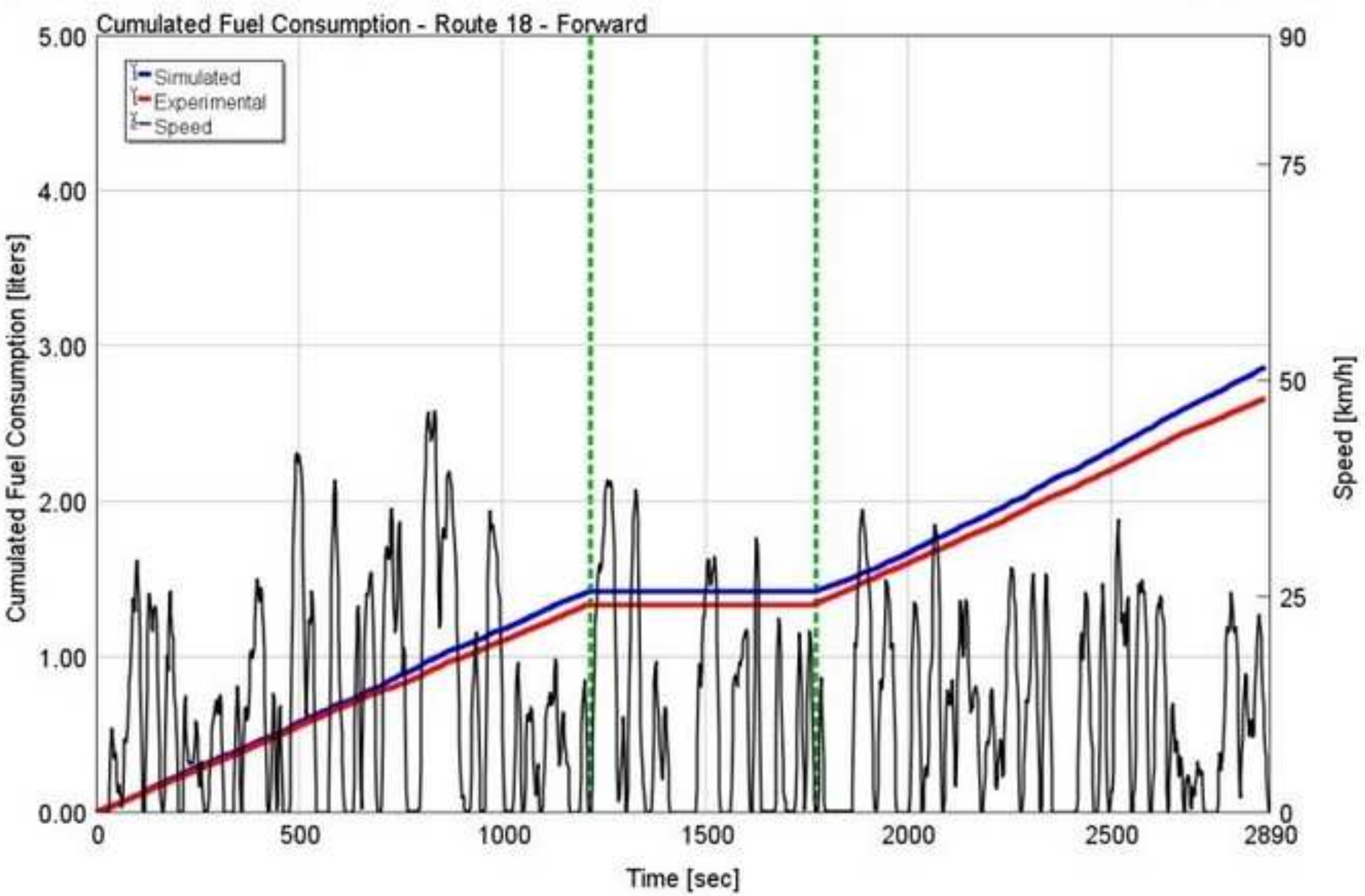

Figure11

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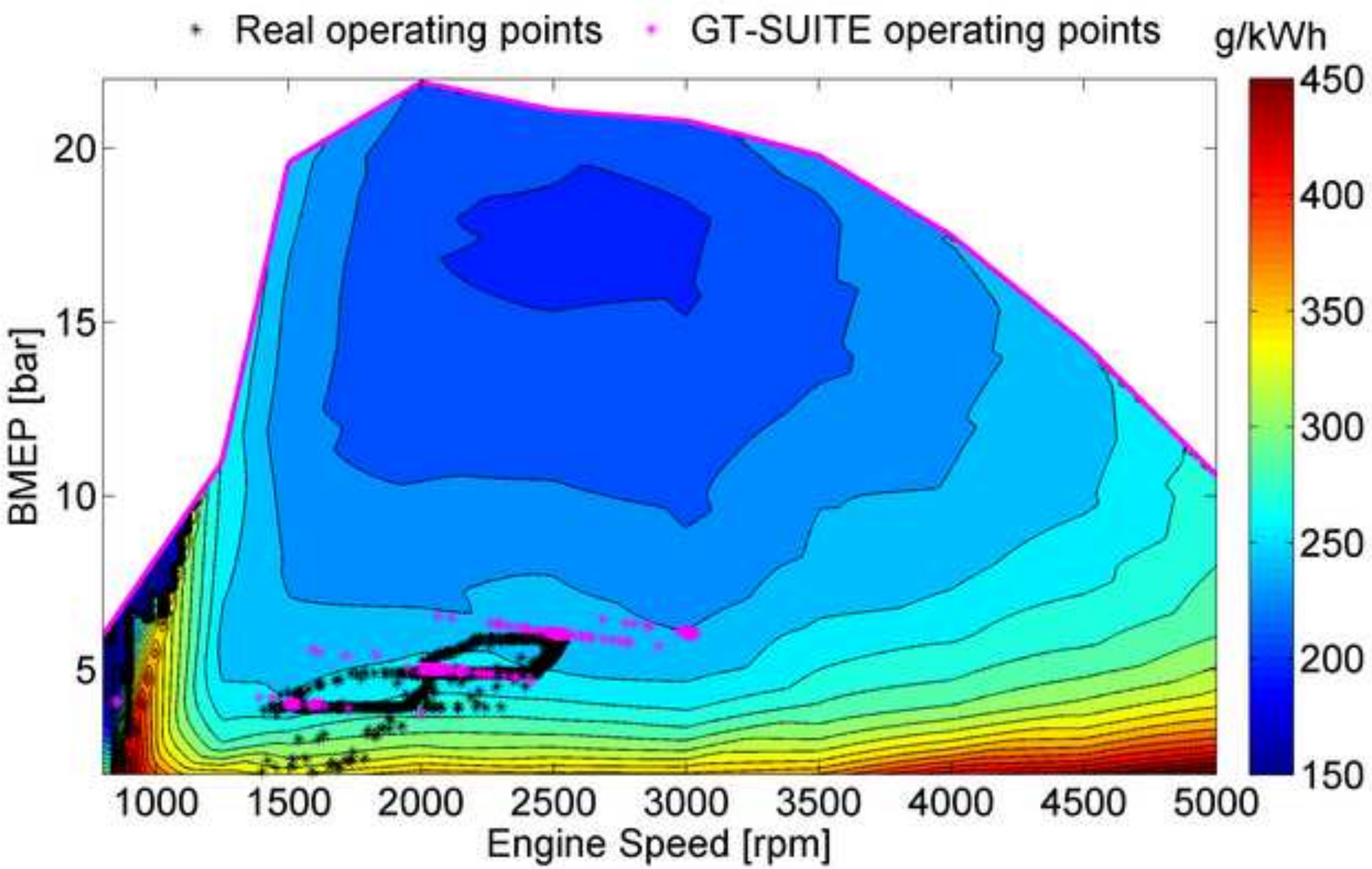

Figure12

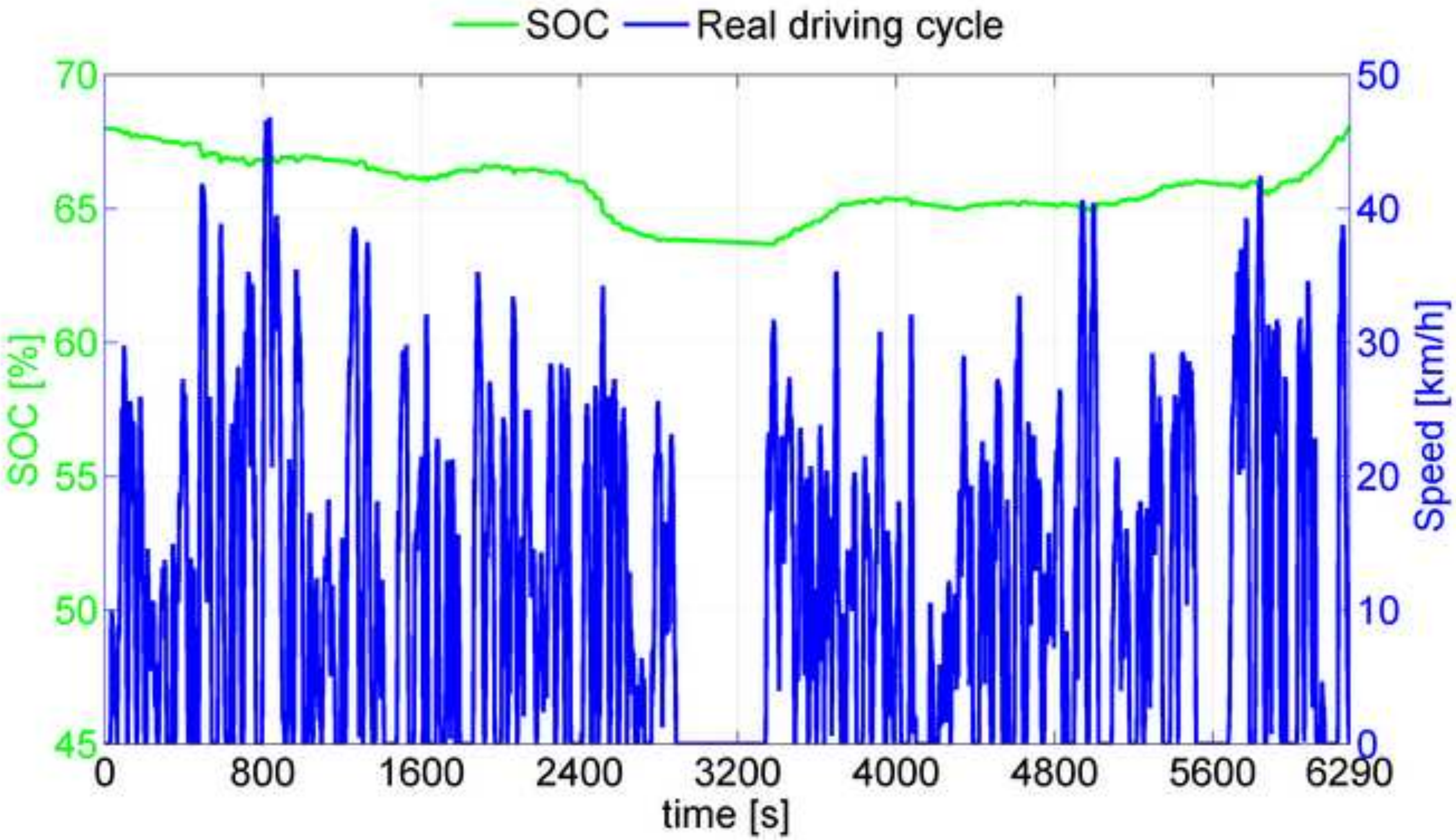
SOC
Real driving cycle
SOC [%]
70
65
60
55
50
45
Speed [km/h]
50
40
30
20
10
0
0
800
1600
2400
3200
4000
4800
5600
6290
time [s]

Figure13

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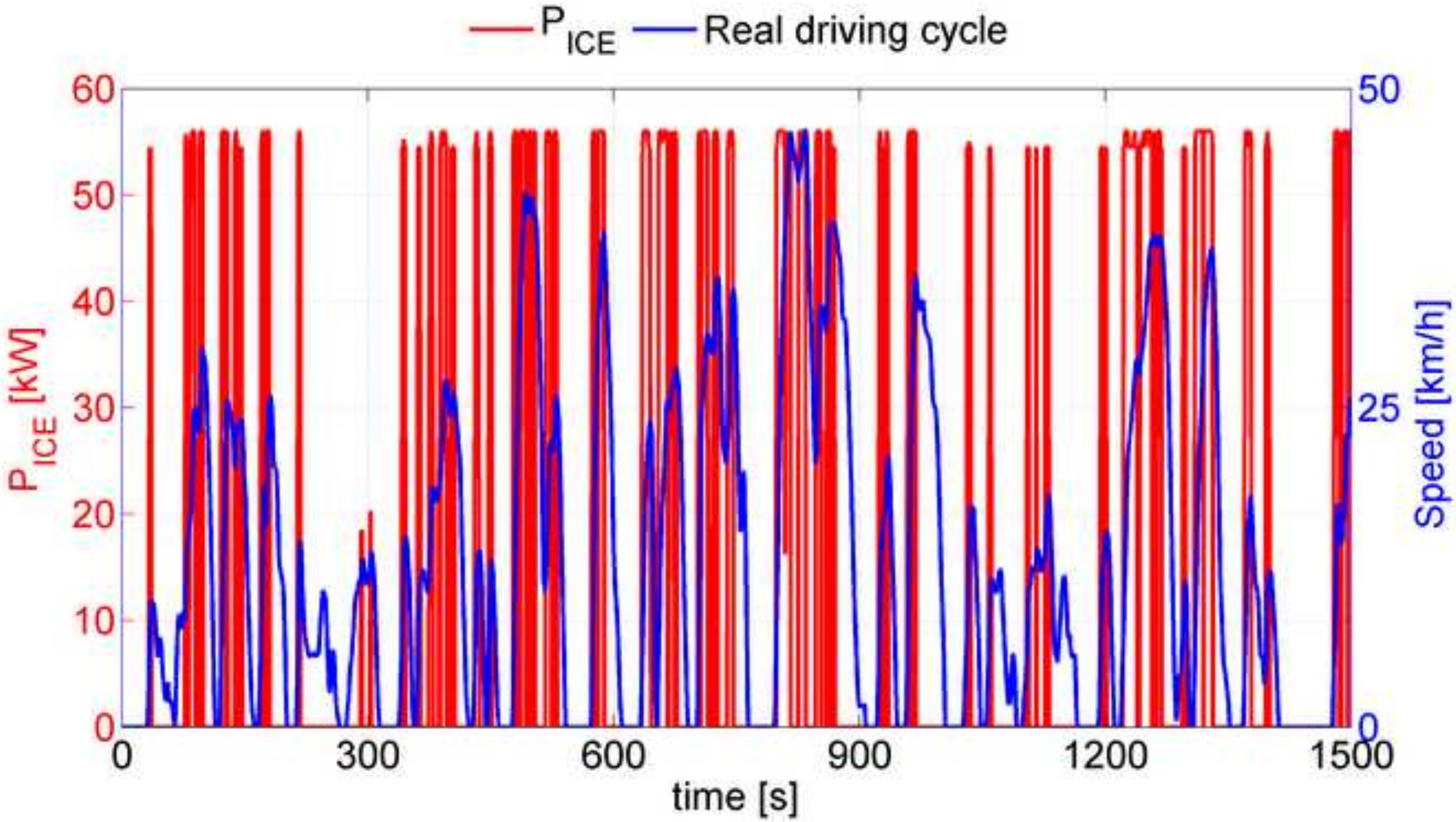

Figure14

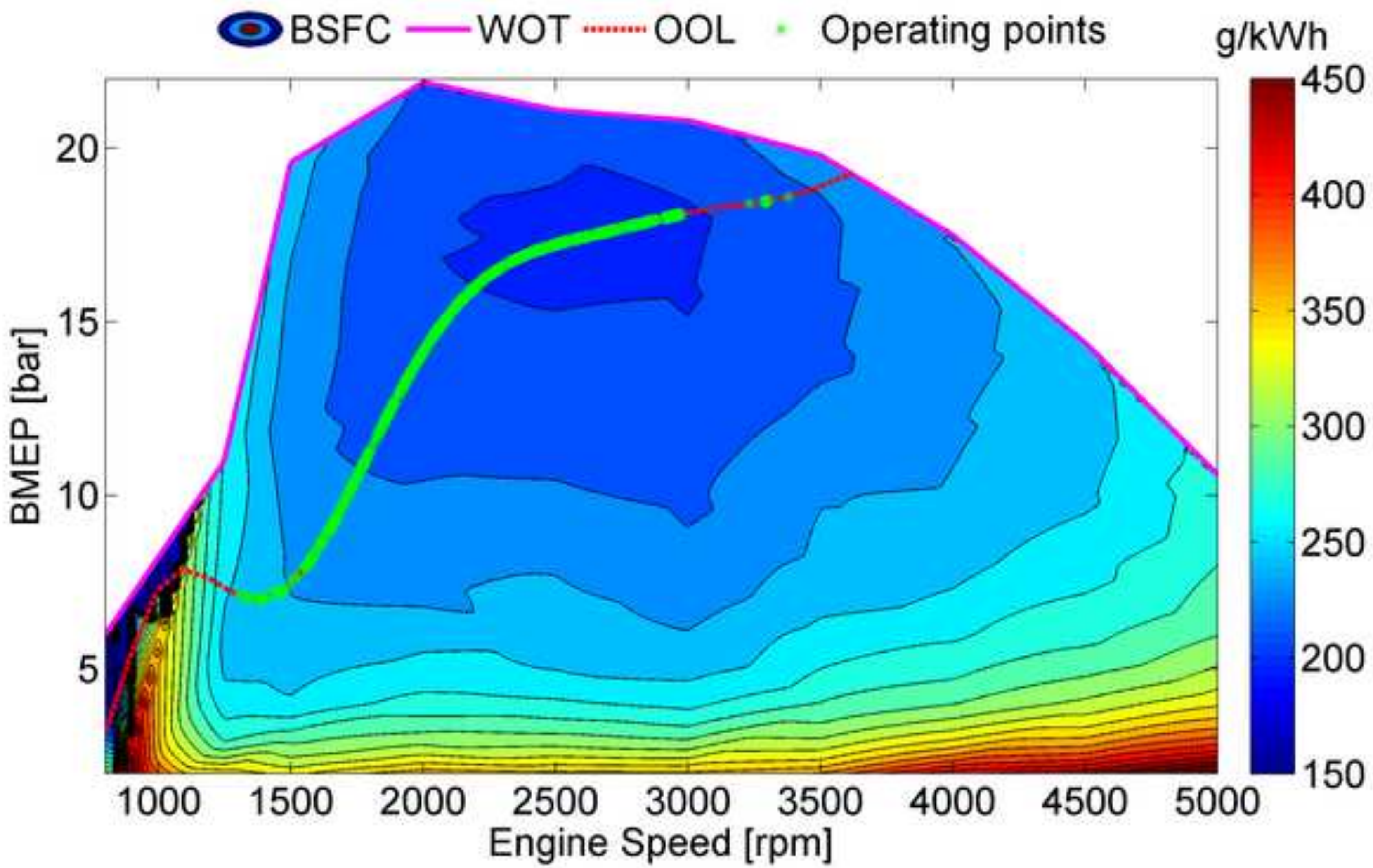
BSFC
WOT
OOL
Operating points
g/kWh
450
400
350
300
250
200
150
20
15
10
5
BMEP [bar]
1000
1500
2000
2500
3000
3500
4000
4500
5000
Engine Speed [rpm]

Figure15

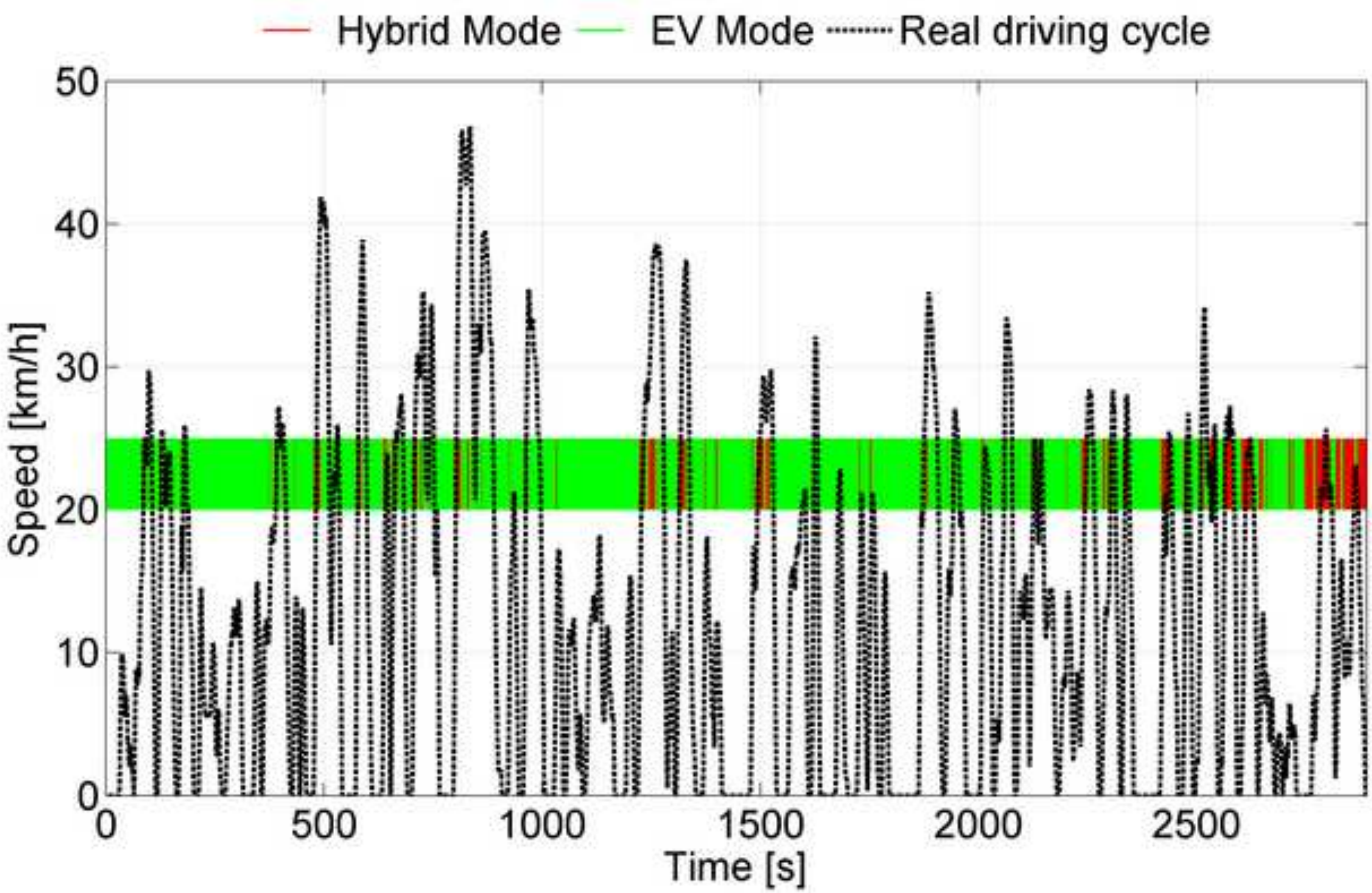
Hybrid Mode
EV Mode
Real driving cycle
Speed [km/h]
50
40
30
20
10
0
0
500
1000
1500
2000
2500
Time [s]

Figure16

Click here to download high resolution image

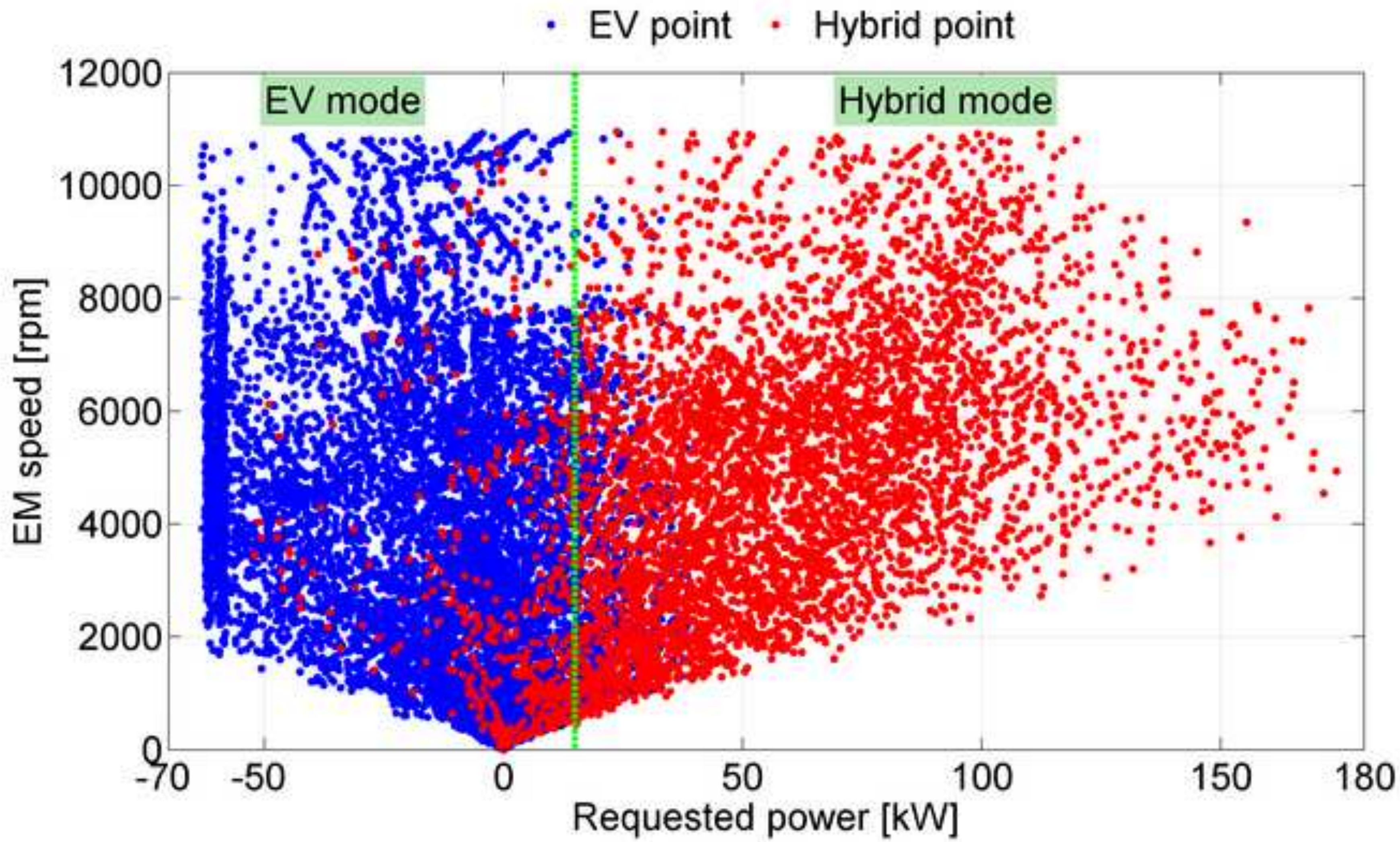

Figure17

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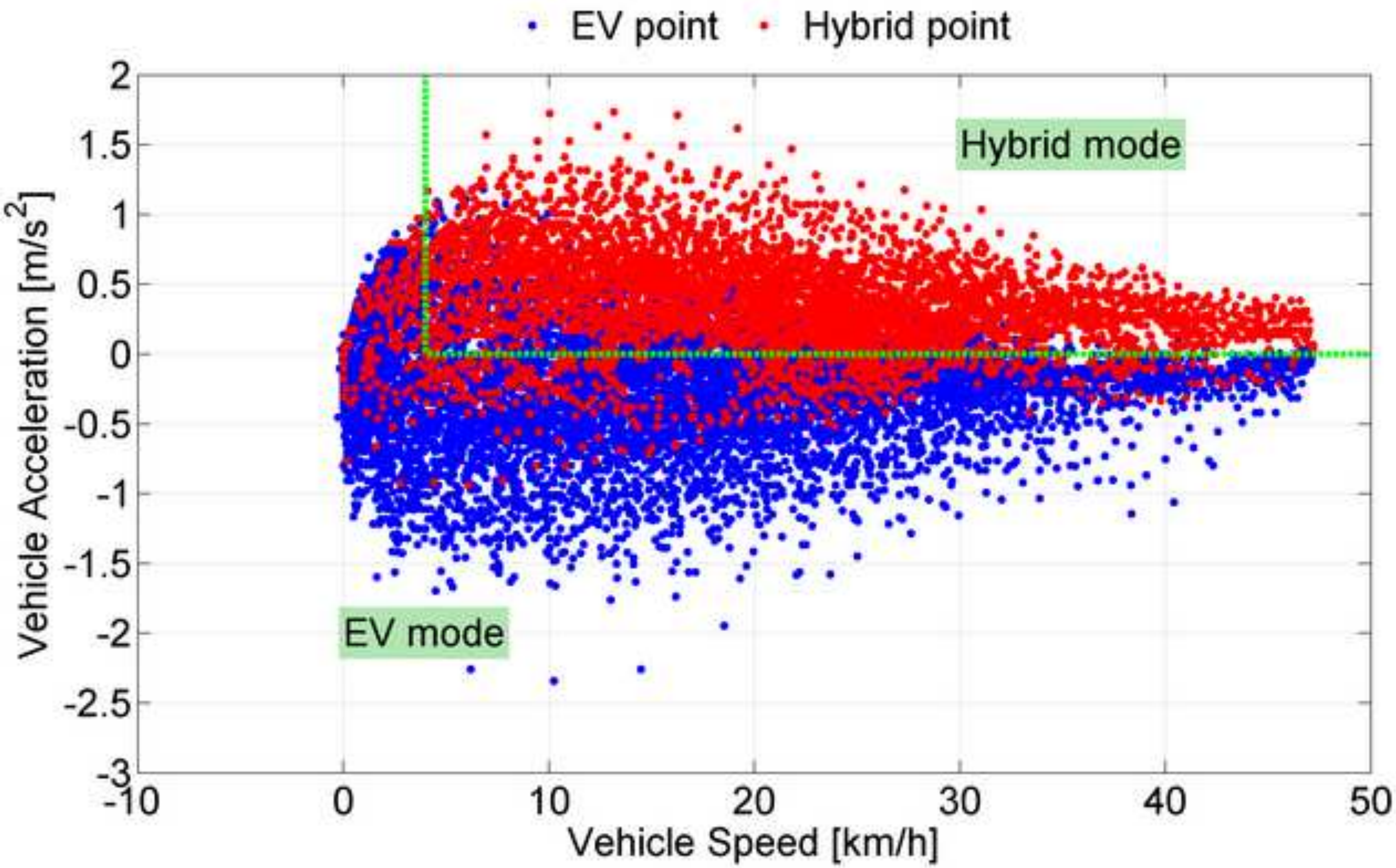

Figure18

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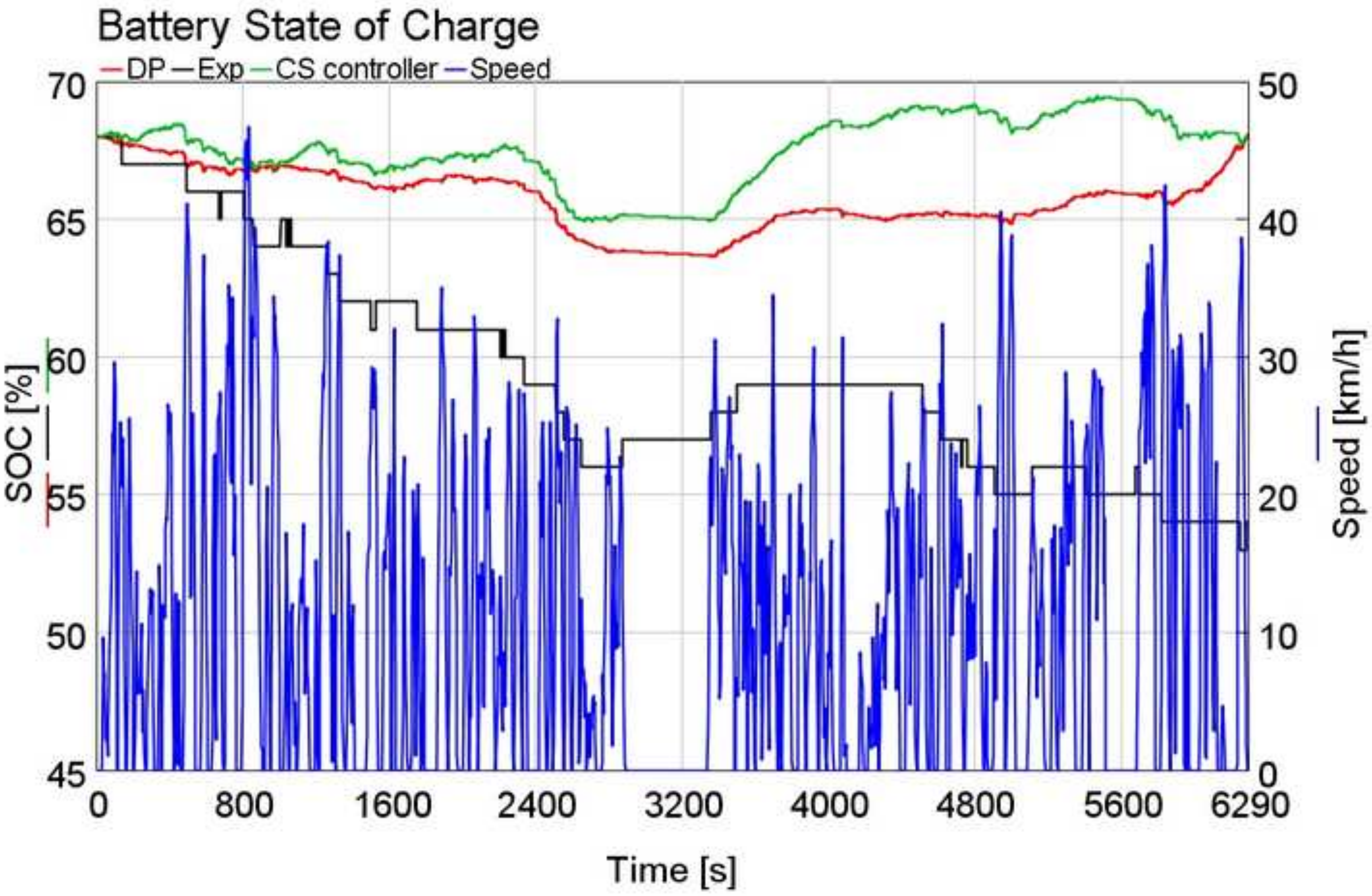

Figure19

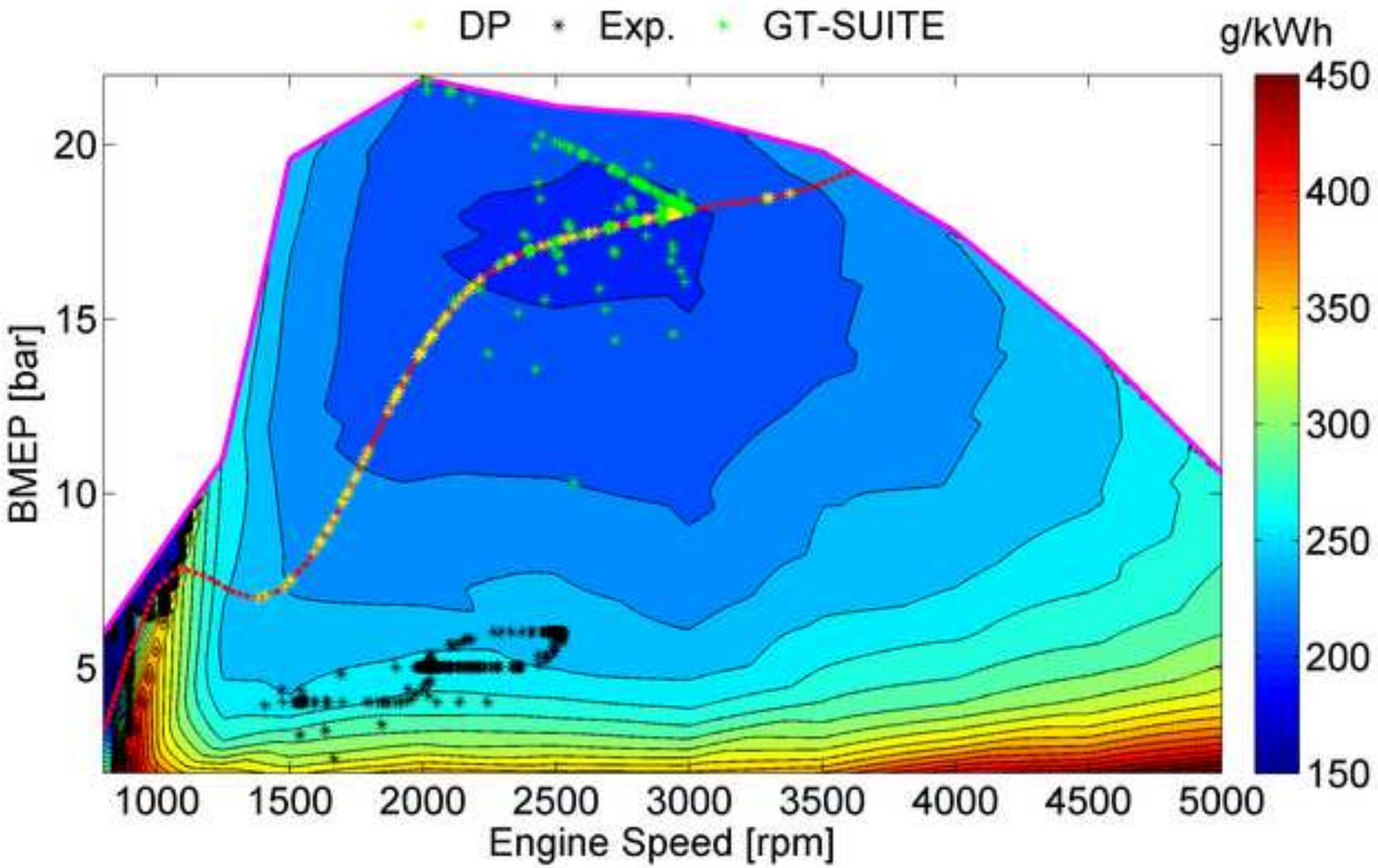
DP
Exp.
GT-SUITE
g/kWh
450
400
350
300
250
200
150
BMEP [bar]
20
15
10
5
1000
1500
2000
2500
3000
3500
4000
4500
5000
Engine Speed [rpm]

Figure20

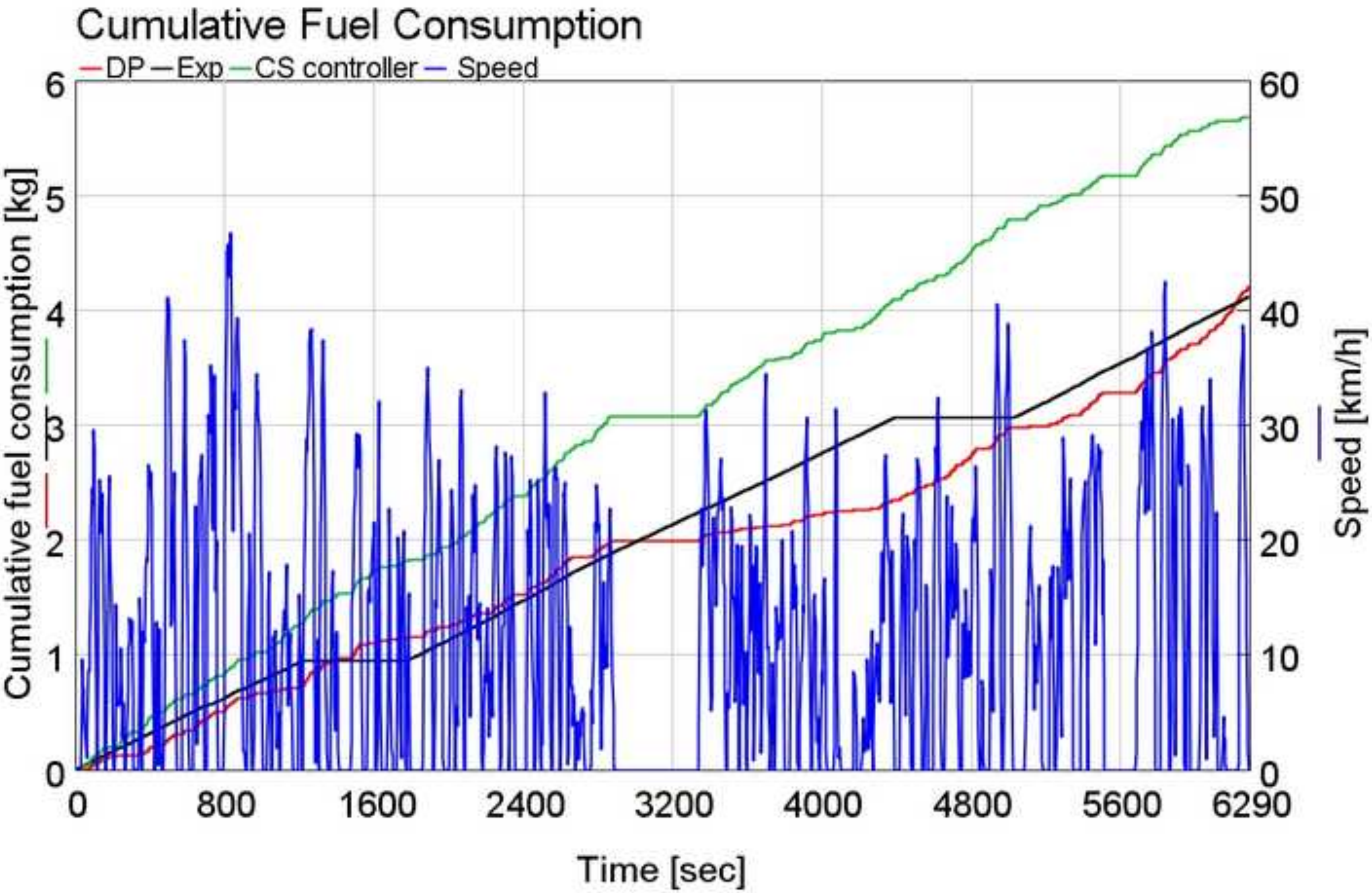
Cumulative Fuel Consumption
DP
Exp
CS controller
Speed
Cumulative fuel consumption [kg]
Speed [km/h]
Time [sec]
0
1
2
3
4
5
6
0
10
20
30
40
50
60
0
800
1600
2400
3200
4000
4800
5600
6290

Table 1. TURBOCITY UR-GREEN data

Dimensions [mm]	12000×2500×3130 (L×W×H)
Wheelbase [mm]	6150
Wheel Track [mm]	Front 2086 Rear 1836
Curb Weight [kg]	11180
Max. Total Weight [kg]	19000
Frontal Area [m^2]	7.5
Drag Coefficient [-]	0.8
Tire Rolling Resistance [N]	$0.006+0.23\times10^{-6}\times V^2$ (with V[km/h])

Table 1. Drivability requirements

Max. Velocity [km/h]	65
Max. Gradeability in full-load [%]	14
Min. Acceleration [m/s^2]	1.1

Table 3. HYBUS powertrain main specifications

Traction Motor:	
Number [#]	2 Parallel Connected
Type	Asynchronous
Mass [kg]	48
Peak Power [kW]	180
Nominal Power [kW]	90
Max Torque [Nm]	185
Nominal Torque [Nm]	145
Max. Speed [rpm]	12000
Nominal Voltage [V]	350
Overall Trans. Ratio (ω_{wh}/ω_{EM})	1/42.5
APU	
Generator	Traction Motor like, directly coupled to the ICE
ICE	
Type	Diesel (Euro 5)
Displacement [cm^3]	1300
Peak Power [kW]	73
Max Torque [Nm]	220
Mass [kg]	236
Battery	
Nominal Voltage [V]	384
Maximum Voltage [V]	438
Minimum Voltage [V]	300
Total Capacity [Ah]	260
Max Discharge Current (< 30s)[A]	600
Max Discharge Current (Cont.) [A]	300
Recommended charge current [A]	140
Total weight [kg]	1230
Max Output Power (kW) (< 30s)	230
Energy [kWh]	99.84

Table 4. Route 18 overall energy consumption data

OVERALL CONSUMPTION	
Fuel Consumption [g/km]	258
Fuel Energy (m_{fuel}LHV) [kWh]	58.3
Battery Consumption [kWh]	13.0
Total cost [€]	9.6

Table 5. Route 63 overall energy consumption data

OVERALL CONSUMPTION	
Fuel Consumption [g/km]	229
Fuel Energy (m_{fuel}LHV) [kWh]	63.6
Battery Consumption [kWh]	11.3
Total cost [€]	10.00
TRANSIT AGENCY CONSUMPTION DATA	
Average Fuel Consumption [g/km]	416
Total cost [€]	14.82

Table6

Table 6. Compared “back-to-back” fuel consumption test on Route 48

FUEL CONSUMPTION	
Scania [g/km]	450
HYBUS [g/km]	330
BATTERY CONSUMPTION	
Scania [kWh]	-
HYBUS [kWh]	9.5
TOTAL COST OF THE TRIP	
Scania [€]	16.38
HYBUS [€]	13.54

Table 7. Model validation: fuel consumption on Route 18-forward

TOTAL FUEL CONSUMPTION	
Experimental [liters]	2.7
Simulated [liters]	2.8

Table 8. Braunschweig cycle simulation: fuel consumption results compared with experimental results for an EEV Irisbus

FUEL CONSUMPTION	
Irisbus [g/km]	340
Irisbus fuel energy (m_{fuel}LHV) [kWh]	43.8
HYBUS [g/km]	182
HYBUS fuel energy (m_{fuel}LHV) [kWh]	23.5
BATTERY CONSUMPTION	
Irisbus [kWh]	-
HYBUS [kWh]	10
TOTAL COST OF THE TRIP	
Irisbus [€]	5.64
HYBUS [€]	3.09

Table 9. Fuel consumption and cost over the real driving cycle

	Fuel (L)	Cost (€)
HYBUS Real test (Charge depleting)	Fuel: 4.83 L Electric Energy: 14 kWh	8.55
HYBUS DP (Charge sustaining)	4.93	6.44
HYBUS novel controller (Charge sustaining)	6.65	8.69
Conventional bus	9.32	12.18

Development of a new hybrid bus for urban public transportation

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Abstract

Nowadays the increasing demand for sustainable mobility has fostered the introduction of innovative propulsion systems also in the public transport sector in order to achieve a significant reduction of pollutant emissions in highly congested urban areas. This paper describes both the design and the optimization of an environmentally friendly hybrid bus (hereafter referred to as “HYBUS”) for urban public transportation.

After a preliminary description of the main features of the hybrid architecture, this paper assessed, through numerical simulations, the fuel economy potential of the hybridization in real world driving conditions. The promising results of this first part of the study led to the development of a first prototype.

The first prototype of the bus was built by integrating an innovative hybrid propulsion system featuring a plug-in series architecture into the chassis of an old IVECO 490 TURBOCITY. The bus is 12 meters long and capable to host up to 116 passengers in the original layout. The project relied on a modular approach where the powertrain could be easily customized for size and power, depending on the specific application.

The prototype was then extensively tested in the city of Genoa, Italy, an urban context extremely challenging for a hybrid powertrain due to its frequent uphill routes and significant road grades. The outcomes of the test campaign confirmed the simulations forecasts, and fostered additional analysis aimed to optimize the energy management strategy of the hybrid powertrain.

Numerical simulations were then used in order to identify more refined energy management strategies capable of further enhancing the fuel economy potential of the hybrid architecture. Consequently, a novel energy management was developed, and virtually tested, to manage the HYBUS in a more effective way. The results demonstrated the interesting potential of such hybrid architecture.

Keywords

Hybrid Electric Bus; CO_2 Emissions; Energy Cost.

1. Introduction

In a context of the global economic downturn, the high demand for sustainable transportation and for cost reduction for transit agencies could meet halfway. Indeed, fuel cost represents one of the most significant portions of transit agency budgets (by way of example for the 2012 for the Turin Transit Agency fuel cost was equal to 22% of sales proceeds [1]) and its reduction directly corresponds to a cut of CO_2 emissions. As a consequence, bus hybridization offers an attractive option in this direction and has the potential to significantly reduce operating costs for agencies.

Simulation tests have highlighted the strong capabilities that different hybrid bus concepts can exploit in terms of better fuel economy [2-4] and lower emissions compared to conventional buses equipped with Internal Combustion Engines (ICEs).

Although the best enhancement in terms of fuel consumption is usually reached by means of powertrain architectures with high flexibility like Hybrid Electric Vehicles (HEVs), to date HEVs had not been widely adopted due to their high costs related mainly to the battery pack. Therefore, sometimes low cost hybridization solutions such as for instance Hybrid Hydraulic Vehicles (HHVs), seem to be more attractive even if they exhibit lower efficiency compared to equivalent electrified powertrains [5].

However, the amount of case-studies focused on hybrid buses and their experimental testing which is available in literature is still limited, although in the last few years it is possible to cite several examples of agencies that are currently employing experimental HEV buses in their fleets [6-11] to assess their real performance. Moreover, fuel economy can vary according to a huge number of factors, including number of stops per unit distance, road grade, surrounding traffic volume and conditions, environmental conditions, driving style, type of hybrid technology, roadway type, and passenger load [12-14].

For these reasons the real fuel economy gain which can be gathered during in-use vehicle operation sometimes leads to results which are very different from those expected.

Finally, it has to be mentioned that an additional barrier to the wider diffusion of hybrid electric buses is represented by their significantly higher purchase cost (approximately 50% to 70% higher) [15] in comparison with conventional diesel urban buses.

The HYbrid BUS (HYBUS) project, carried out in cooperation between Politecnico di Torino and Pininfarina, Italy, aims therefore to address the abovementioned issues, trying to reduce both the fuel consumption and the purchase cost of a new, environmentally friendly urban bus, which has been conceived through the study of a modular hybrid propulsion system, allowing the conversion of old vehicles currently equipped with Euro 0–1–2 diesel engines into buses with serial hybrid power packs.

The core idea of the project is to exploit the older buses present in the agencies' fleets, which can be still fully functional, but with pollutant emission rates too high to comply with current legal limitations: in the HYBUS the original diesel powertrain of an old IVECO 490 TURBOCITY (12 mt. long, 116 passengers urban bus) was removed and replaced by a new generation plug-in series hybrid powertrain. Moreover, thanks to the modularity of the proposed hybrid architecture, the powertrain could be adapted to different types of urban busses.

The cost saving is estimated to be about 50% compared to a new conventional diesel bus (for which a price estimate between 220-290 k€ can be made[16-17]) and about 60% compared to a new hybrid bus (for which a price estimate of about 350 k€ can be made [18-19]).

Such an approach could obviously not be considered the ultimate solution towards the green urban mobility: however, although a retrofitted bus, will not last as long as a new hybrid bus, with its upfront savings compared to a factory-new solution, it could pave the way to a fast upgrade of the fleets, allowing a gradual and affordable introduction of new advanced HEVs.

This article describes in the next Section 2 the steps that led to the HYBUS prototype production, from the concept idea to the design and manufacturing, as well as the first testing phases under real world operating conditions in the city of Genoa, Italy. Afterwards, in Section 3 the set-up, validation and exploitation of a numerical model of the HYBUS is described, in order to assess the potential of the selected hybrid powertrain in terms of fuel economy and to provide a virtual test rig for the development of more advanced energy management strategies, which are discussed in the last Section 4.

2. HYBUS Development and Experimental Assessment

2.1. Powertrain Requirement Evaluation

The revamping of a bus, with the goal to realize a completely new powertrain, requires the knowledge of the typical mission profile and of the main features of the vehicle.

For these reasons the first step of the project was the identification of a bus potentially suitable for the task. After a brief research among the Turin transit agency's fleet [20], the IVECO TURBOCITY UR-GREEN – EURO 1 was selected since it represented the largest fraction of the older buses in the agency's fleet, and by upgrading this model alone, more than 10% of overall vehicles of the Turin transit agency [21] could reduce their environmental impact in the city center.

The main features of the vehicle are summarized in Table 1.

As far as the driving pattern is concerned, the Standardized On-Road Test Cycles (SORT) 1 (Heavy Urban) and SORT 2 (Easy Urban) cycles [22] were initially used to obtain, through a simple kinematic model [23], a first estimate of the vehicle road load during typical operating conditions.

Although traction power peaks during the abovementioned test cycles can be larger than 150 and 200 kW, the average traction power levels do not exceed 6 and 10 kW, respectively on SORT1 and SORT2 [2].

Benchmarking analysis on other buses of the same category led to set the additional quantitative targets which are reported in Table 2.

2.2. Main HYBUS Characteristics

A series hybrid architecture was chosen in order to allow the revamping of the vehicles independently from the characteristics of the buses owned by the transit agencies. Indeed, owing to the different layouts of the engine compartment, a different placement of the equipment could be necessary to satisfy requirements such as cooling, fuel supply, and safety without major modifications of the original chassis. From this point of view, a series hybrid powertrain is extremely flexible: the only constraints are the connection of the electric traction motor with the vehicle transmission and a mechanical connection between the internal combustion engine and the electric generator to realize the Auxiliary Power Unit (APU). All the other power links, being electrical, can be tailored for the specific application. A scheme of the connections between the main hybrid powertrain components is shown in Figure 1.

To achieve the objectives of modularity and easiness of updating, the main components of the powertrain were placed within aluminum frame structures, with anchorage points that can be adapted to different types of vehicles. Within each structure each component can be fixed by standardized brackets allowing an easy maintenance.

Once the power/energy requests and the additional drivability specifications were evaluated, as described in previous section 2.1, the components and the main features of the vehicle powertrain were selected (Table 3).

Considering a typical urban daily mission profile, an average energy requirement of about 5 MJ/km was estimated [24]; consequently, a battery pack of about 100 kWh was chosen to avoid excessively “deep” discharges (design specifications of the battery allow a peak discharge current of 600 A for at most 30 seconds) that could dramatically reduce battery life. Indeed, such a capacity allows the possibility to run on several routes before to recharge the plug-in vehicle at the bus end of line.

For the battery modules a Lithium Iron Magnesium Phosphate technology was chosen as the most suitable for this type of application. This technology chimes with the automotive requirements for a battery [25]. Among the benefits, are worth to be noted the high number of recharging cycles with deep discharge allowed during the battery life; a naturally good “thermal management”, reducing the on-board cooling requirements; extremely low self-discharge rate, limiting battery depletion after several days of stop; fast and safe recharging capabilities. An overall sketch of the system is depicted in Figure 2, where the main powertrain components are highlighted in blue.

As far as the choice of the ICE is concerned, a specific study to identify the best trade-off between fuel consumption, pollutant emissions and engine size was carried out [2],[26]. Since in a series hybrid architecture the internal combustion engine has only to provide the average power requested by the vehicle, a small displacement automotive ICE (1.3 liter) was selected, in order to fully exploit the potential offered by engine downsizing.

2.3. Testing Activities

After the preliminary evaluations carried out through numerical simulation, the first HYBUS prototype was built in the Pininfarina facilities (see Figure 3) and the real potential of the HYBUS architecture in terms of fuel economy was then verified with an extensive test campaign on the routes of the Italian city of Genoa, in cooperation with the local transit agency. The city is composed of a thin coastal strip behind which hills and mountains rise: this peculiar geography produced highly heterogeneous city roads, going from flat sections to steep climbs with grades up to 15 %. Consequently the daily routes of the local buses represent a quite challenging test for a series hybrid powertrain as well as for its energy management strategy.

Among these urban routes several were tested with the vehicle fully ballasted and in the following sections some brief excerpt of the most meaningful tests will be analyzed.

It is worth to be mentioned that these experimental tests were the first on-road experiences of the HYBUS prototype. Therefore the VMU (Vehicle Management Unit) dataset's variables were precautionary limited to avoid any reliability issue, limiting for instance the maximum vehicle speed at 50 km/h.

Pure Urban - Route 18

Route 18 is representative of the usage in a pure urban context: traveling through the most congested streets of the city (with an average speed of about 11km/h on its 9.4 km of length and a variable grade between ± 5%), with a lot of stops at traffic lights and continuous bus stops due to the high number of passengers (about 3.5 stops/km on average), this usage undoubtedly represents a challenging benchmark for conventional buses. The energy requirement of 2.75 MJ/km on this route confirms the conservative assumption made in paragraph 2.2. Besides the severe gradeability requirements, an increased power absorption from the ancillaries systems has also to be taken into account, due to the continuous usage of brakes and doors openings (which are pneumatically assisted), leading to an intensive activity of the air compressor.

One of the real mission profiles acquired during the experimental activity is shown in Figure 4. A restricted traffic area was also considered during the trip, switching-on the pure electric propulsion. The SOC depleting resulting from the trip is shown in Figure 5.

Taking into account both the forward and backward travel, and adopting the prices paid by the transit agency for electricity (0.16 €/kWh) and for diesel fuel (1.31 €/l) at time when tests were carried out (June 2012), the overall energy consumption data of the HYBUS are summarized in Table 4. In particular the vehicle exploited 13 kWh of energy from the battery and a fuel consumption of 258 g/km from the ICE. Unfortunately the real fuel consumption data of the conventional buses on this route were not available, but considering the average mileage value of 1.5 km/l registered by Genoa transit agency, the total cost for each complete round trip on route 18 for a conventional diesel bus will lead to more than 16 €, highlighting the impressive savings of the HYBUS.

Urban & Suburban Mix - Route 63

After the urban tests previously described, an urban & suburban mix was tested on Route 63, which is representative of a commuter usage, with two urban sections connected by a central suburban piece. The total length of the round trip is about 23.3 kilometers, with an average speed of about 19 km/h, and the grade profile (with a peak of 5%), together with a real speed profile, is depicted in Figure 6. The SOC depleting resulting from the trip is shown in Figure 7.

Also in this case the fuel and cost savings achieved by the HYBUS in comparison with a conventional bus (data provided by Genoa transit agency) were impressive, as shown in Table 5. In this case an average fuel consumption of 229 g/km was obtained by the HYBUS and 11.3 kWh were drawn from the battery.

These results are even more impressive when considering that the APU working points were kept, as a precautionary measure, in the lower part of the engine map, as shown in Figure 8, in order to avoid excessive stresses on the engine and on its cooling system, due to the high environmental temperatures (test were carried out during the month of July).

Therefore the efficiency of the APU could be further improved in the next version of vehicle, leading to an extra reduction of the fuel consumption. For these reasons further numerical simulations were performed in the following to evaluate the improvements that could be obtained with a refined energy management system without precautionary limits on the APU operation.

Compared “back-to-back” fuel consumption test

In order to complete the assessment of the HYBUS performance also a comparative “back-to-back” test was performed: a city route, the urban Route 48, was performed with the HYBUS running first, immediately followed by a conventional bus, so to have the same traffic conditions, measuring at the end the overall fuel consumption of the two vehicles. Although the aerodynamic drag of the second bus was affected by the HYBUS, for this comparison these effects could be neglected, considering the low speeds reached during the test. The conventional bus was a 12 meters long Scania CV AB Omnicity, selected among the newest part of the Genoa Transit agency fleet. Both the vehicle were ballasted to reach about 16 tons each.

The fuel consumption was measured starting with the full tanks for both the buses and refilling them at the end of the journey; the consumptions are summarized in Table 6. Considering the entire cost of fuel and electricity, the HYBUS saved more than 2€ compared to the Scania

3. Numerical Simulation of the HYBUS

Once the global features of the HYBUS were defined, extensive simulations were carried out in order to assess the potential of the selected hybrid powertrain in terms of fuel economy and to provide a virtual test rig for the development of more advanced energy management strategies.

However, before the simulation model could be used for these analysis, it had to be validated against experimental measurements, and the data collected during the Genoa campaign were therefore used as a reference for this purpose.

Finally, it is worth to be pointed out that, as far the assessment of the fuel economy potential is concerned, the HYBUS simulation results were not compared with the performance of the original bus, but rather with state of the art, EEV (Enhanced Environmentally-friendly Vehicle) buses of the same class, with which the HYBUS should compete on the market when transit agencies would need to update their fleets.

3.1. Model set up

Computer simulations were carried out by means of a vehicle model developed in GT-Drive [27-29], where the internal combustion engine and the electric machines are represented through performance maps, which were experimentally measured under steady state operating conditions. Hence, although system dynamics are taken into account, the simulation model follows a “quasi-static” approach, because engine and electric machines behavior is described by steady state maps. This simulation approach has been demonstrated to be appropriate for the evaluation of instantaneous fuel consumption of light-duty vehicles [30] over the most common regulatory driving cycles, due to the moderate speed (typically between 0 – 130 km/h) and load transients which are usually prescribed, while the assessment of the simulation accuracy for urban buses driving cycles has been discussed in previous works of the research group, such as for instance in [31].

Driver behavior is represented through the use of a Proportional-Integral-Derivative (PID) controller aiming to follow the driving cycle schedule. A BMS (Battery Management System) handles the electric power flow avoiding dangerous overcurrent and aiming to maximize battery life by controlling the charge-discharge cycles of the battery pack.

Furthermore, during decelerations the braking controller exploits the traction electric motors to regenerate a part of the kinetic energy of the vehicle. The remaining of the braking energy required is provided by conventional brakes.

Finally, an APU Controller Unit manages the system according to a simple rule-based power management strategy.

3.2. HYBUS Model Validation

The experimental data collected during the Genoa campaign were used to validate the HYBUS model.

For this purpose the speed and grade profiles of the Forward route 18 have been used as model inputs, together with the experimentally measured auxiliary power absorption.

The agreement between the numerical and experimental results is quite satisfactory, as one can see from Figure 9 and 10, as well as from data reported in Table 7.

The ICE operating points are depicted in Figure 11. Results from the model are in relatively good agreement with the experimental data, although some discrepancies can be clearly seen, due to unavoidable differences in the implementation inside the real ECU. However, the gap in the total fuel consumption over the trip is limited, as summarized in Table 7, and the model accuracy can thus be considered as satisfactory.

3.3. HYBUS potential assessment through numerical simulation

The HYBUS fuel consumption results obtained through numerical simulation were then compared with the experimental results obtained by an Irisbus CITELIS S Diesel EEV bus, on the same driving cycle [32], as summarized in Table 8.

A noticeable fuel saving of the HYBUS compared to the Irisbus equipped with a conventional powertrain was observed, with a total fuel saving of 46 %. Obviously one of the drawbacks of the plug-in hybrid vehicle is the battery energy depletion, which, in this case, is estimated as 57% of the fuel energy. On one hand the contribution of the battery reduces the local pollutant emissions, but on the other hand, the financial saving of this solution depends on the price of the electricity for the transit agency. Nevertheless the HYBUS allows an impressive 45% energy cost saving compared to the Irisbus. However, it has to be pointed out that, in order to enable the achievement of such results, it should be possible to recharge the HYBUS battery from the grid at the end of the line stops and/or at the garage overnight: this could represent an issue for transit agencies, since all end of the line stops and garages should be equipped with chargers and safety problems due to the high voltage should be managed. For this reason, the capability of the HYBUS to operate in charge sustaining mode was also explored in a later phase of the project, as discussed in the following Section 4.

4. Energy Management Strategy development

After the validation of the simulation model, further improvements of the energy management strategy were then investigated numerically, since the optimal control of the power flows in a hybrid vehicle is one of the keys to obtain a significant advantage in terms of fuel consumption.

Usually, due to the a-priori knowledge of the mission profile and the high computational requirements, Energy Management Strategies (EMS) optimization cannot be performed in real-time on hybrid vehicles. Nevertheless, for urban buses the mission profile can be known a-priori, at least to a certain extent, thus paving the way to the development of “route-tailored” energy management strategies. Therefore, a sub-optimal controller was developed based on heuristic rules, which were determined on the basis of the analysis of the results obtained by means of Dynamic Programming (DP) simulations. For this purpose, a forward and backward trip, of a real driving cycle representative of a specific route of the Genova transit agency was used.

4.1. Dynamic Programming – Modelling Approach

DP generates a numerical solution for an optimal control problem and it gives sufficient conditions for the global optimality. It is based on Bellman's principle of optimality [33] and is able to manage a dynamic model of the system; since DP is commonly used to solve time-continuous control problems, the model has to be discretized in a sequence of time steps for which DP is capable of determining the optimal control laws. In this work, an open-source MATLAB code developed by the ETH-Zurich [34] was used for the optimization and coupled with a simplified kinematic model of the vehicle.

The energy management can be optimized through DP using cost functions focused on different targets, such as for instance the minimum fuel consumption or the minimum pollutant emissions over a certain cycle. In this case, since the simple minimization of the fuel consumption is not a suitable target for a plug-in hybrid, the cost function was defined aiming to minimize the overall CO_2 emissions, including both emissions generated by the fuel burned by the ICE and the equivalent emissions due the electrical energy consumption from the battery (which will have to be the recharged from the grid) along a real driving cycle. Previous studies [35] have highlighted that this approach will lead also to the minimization of the total cost of the fuel and of the electricity. Therefore, the cost function to be minimized can be written as:

$$\min J = \int_0^T \left(\dot{CO}_{2\,f}(t,u(t)) + \dot{CO}_{2\,e}(t,u(t)) \right) dt \qquad (1)$$

with:

$$\dot{CO}_{2\,f} = \frac{\mu_{CO_2}}{\mu_{fuel}} \cdot \dot{m}_f \qquad (2)$$

$$\dot{CO}_{2\,e} = k_{CO_2} \cdot \dot{SoC} \cdot E_{Batt,Norm} \qquad (3)$$

where J is the cost-to-go function, $CO_{2,f}$ is the instantaneous CO_2 emission rate due to the burned fuel and thus is determined by the instantaneous fuel rate $\dot{m}_f$ with the knowledge of molar masses of CO_2 and fuel; $CO_{2,e}$ is the equivalent CO_2 emission rate arising from the instantaneous State Of Charge (SOC) variation of the battery, which can be estimated using equation (3) by means of the nominal energy of the battery $E_{Batt,Norm}$ and the CO_2 conversion factor k_{CO_2}; $u(t)$ is the vector of the control variable and T is the period corresponding to the duration of the driving cycle.

Although the HYBUS is a plug-in HEV and its battery could be recharged by the grid at the end of the day or at end of line stops, due to the issues and of the modifications that should be necessary to the infrastructure, in order to evaluate the fuel economy improvements which could be achieved by the HYBUS without any modifications of the infrastructures, the operation of the HYBUS in charge-sustaining mode was also simulated.

Finally it should be pointed out that, after removing the constraints applied to the ICE during the experimental tests to preserve the first prototype of the HYBUS, was now free to operate on its Optimal Operating Line (OOL), as shown in Figure 14, corresponding to the minimum Brake Specific Fuel Consumption (BSFC).

4.2. Dynamic programming – Results & Rule Extraction

The starting point to define a rule based energy management strategy is the analysis of the optimal strategy identified through the DP. The results obtained through the DP can as a matter of fact provide helpful information concerning the decisions that can be implemented in the rule based algorithm.

The SOC variation determined by the DP are shown in Figure 12 over the entire real driving cycle: it can be clearly seen that, with an initial value of the SOC equal to 0.68, the DP proved to be able to guarantee the charge sustainability. A zoomed in portion of the driving cycle is also reported in Figure 13, showing the requested power from the internal combustion engine: the most frequently requested power is about 56 kW, while the working points are exclusively located on the OOL as shown in Figure 14. Finally, the choice between the two different operating modes, i.e. pure Electric Vehicle (EV) and Series Hybrid mode, operated by the DP is shown in Figure 15: it is pretty evident that series hybrid mode is mainly exploited when the power demand is high, e.g. during strong accelerations.

The operating modes selected by the Dynamic Programming were then further analyzed in order to point out any dependencies from significant input variables, which could be useful to extract a set of rules for a rule-based energy management strategy to be implemented in the VMU: some results of these analysis are shown in Figures 16 and 17. It is quite clear that the hybrid mode is mainly exploited during vehicle accelerations, at speeds higher than 4 km/h, and at high power requests levels, higher than 13 kW. However, it was not possible to infer any dependence of the operating mode selection from the battery state of charge. Therefore, a simple SOC threshold was established to choose between EV and hybrid mode selection when the battery is almost depleted.

4.3. Rule based strategy performance evaluation

After extracting a set of rules from the analysis of the Dynamic Programming and implementing these rules in a heuristic energy management strategy, its performance was evaluated against both DP and experimental results.

It is worth to be recalled however, that, while the newly developed heuristic strategy and the DP are both aiming to achieve a charge sustaining condition, the only experimental results available for the comparison were obtained in charge depleting mode during the previous phases of the project.

The new controller was able to manage the SOC and guarantee the charge-sustainability (see Figure 18). On the other hand, it is worth to be noticed that during the experimental test on the field in Genova the final SOC decreased to 54%. Consequently, the electrical energy consumed over the real driving cycle was about 14 kWh, with a specific electricity consumption of 0.75 kWh/km.

Moreover, it should be pointed out that, due to the engine’s limitation on the HYBUS prototype, the instantaneous power of the ICE was restricted to 5 to 15 kW during the experimental tests, while both the DP and the newly developed control strategy were capable to operate the ICE in the high load and high efficiency zone of the map, as shown in Figure 19.

The cumulative fuel consumption is shown in Figure 20. While the real test achieved the minimum fuel consumption, with 4.12 kg, the additional energy consumption in terms of battery depletion should be taken into account, in order to allow a proper comparison between charge sustaining and charge depleting strategies.

A comparison regarding the total cost over the driving cycle is reported in Table 9. The experimental test achieved a 29.8% reduction compared to a conventional bus, while for the novel controller the improvement was of 28.7%. Therefore, the strong improvement introduced by the first HYBUS prototype could be maintained also with the notable limit on the battery SOC and avoiding the need of charging phases in the garage at the end of the day.

5. Conclusions

A prototype hybrid urban bus, called HYBUS, was built by integrating an innovative hybrid propulsion system featuring a plug-in series architecture into the chassis of an old diesel bus.

The prototype was then extensively tested in the city of Genoa, Italy, an urban context extremely challenging for a hybrid powertrain due to its frequent uphill routes and significant road grades.

The main outcomes of the tests were the followings:

- The HYBUS prototype system allowed fuel consumption reductions ranging from 27 % up to 45 % respectively, if compared with the newest buses or with the average buses of the Genoa transit agency fleet.
- Considering the current costs of diesel fuel and of electricity, and the amount of electric energy needed to restore the battery state of charge of the HYBUS at the end of the trip, the money savings corresponding to the abovementioned fuel savings were equal to 17% and 33% respectively.
- The HYBUS hybrid propulsion system demonstrated to be suitable also for urban routes with significant grades.

- Numerical simulations proved that issues related to the battery recharge can be solved by introducing a new charge sustaining control strategy, while maintaining significant operating cost reductions in comparison with busses equipped with conventional diesel powertrains.

In conclusion the HYBUS was proved to represent an effective way to reduce fuel consumptions and operating costs of transit agencies' fleets, offering an interesting option for the revamping of the oldest buses.

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8. Definitions and Abbreviations

APU	***AUXILIARY POWER UNIT***
BMEP	***BRAKE MEAN EFFECTIVE PRESSURE***
BMS	***BATTERY MANAGEMENT SYSTEM***
BSFC	***BRAKE SPECIFIC FUEL CONSUMPTION***
DP	***DYNAMIC PROGRAMMING***
EEV	***ENHANCED ENVIRONMENTALLY FRIENDLY VEHICLE***
EM	***ELECTRIC MOTOR***
EMS	***ENERGY MANAGEMENT SYSTEM***

EV	***ELECTRIC VEHICLE***
GTT	***GRUPPO TORINESE TRASPORTI***
HEV	***HYBRID ELECTRIC VEHICLE***
HHV	***HYDRAULIC HYBRID VEHICLE***
ICE	***INTERNAL COMBUSTION ENGINE***
OOL	***OPTIMAL OPERATING LINE***
PID	***PROPORTIONAL INTEGRAL DERIVATIVE***
SOC	***STATE OF CHARGE***
SORT	***STANDARDIZED ON-ROAD TEST CYCLES***
VMU	***VEHICLE MANAGEMENT UNIT***

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