

Development of a new hybrid bus for urban public transportation

Original

Development of a new hybrid bus for urban public transportation / Millo, Federico; Rolando, Luciano; Fuso, Rocco; Zhao, Jianning. - In: APPLIED ENERGY. - ISSN 0306-2619. - STAMPA. - 157:(2015), pp. 583-594.
[10.1016/j.apenergy.2015.03.131]

Availability:

This version is available at: 11583/2656765 since: 2016-11-21T15:22:05Z

Publisher:

Elsevier Ltd

Published

DOI:10.1016/j.apenergy.2015.03.131

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Elsevier preprint/submitted version

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<http://doi.org/10.1016/j.apenergy.2015.03.131>

(Article begins on next page)

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

Figure1

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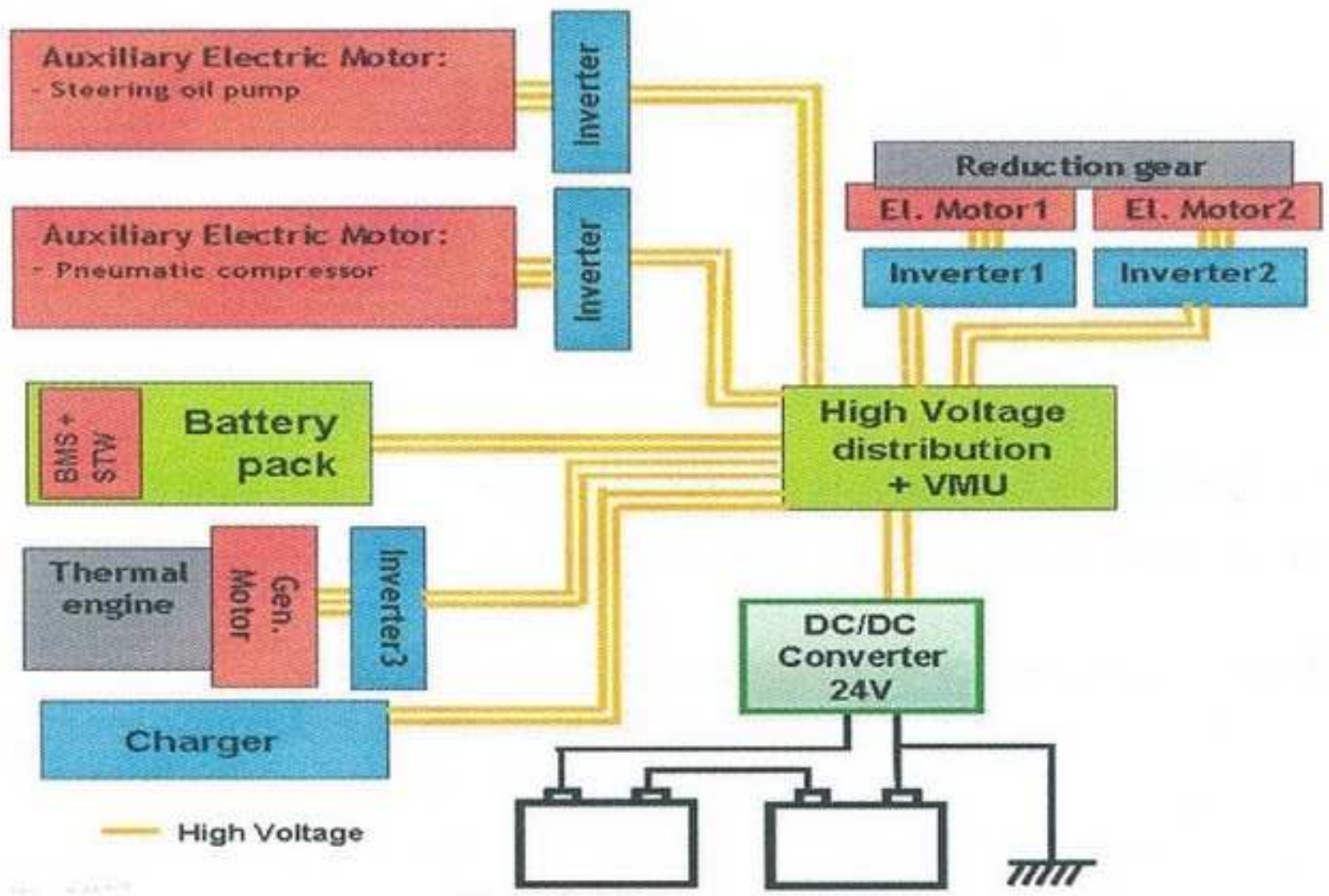


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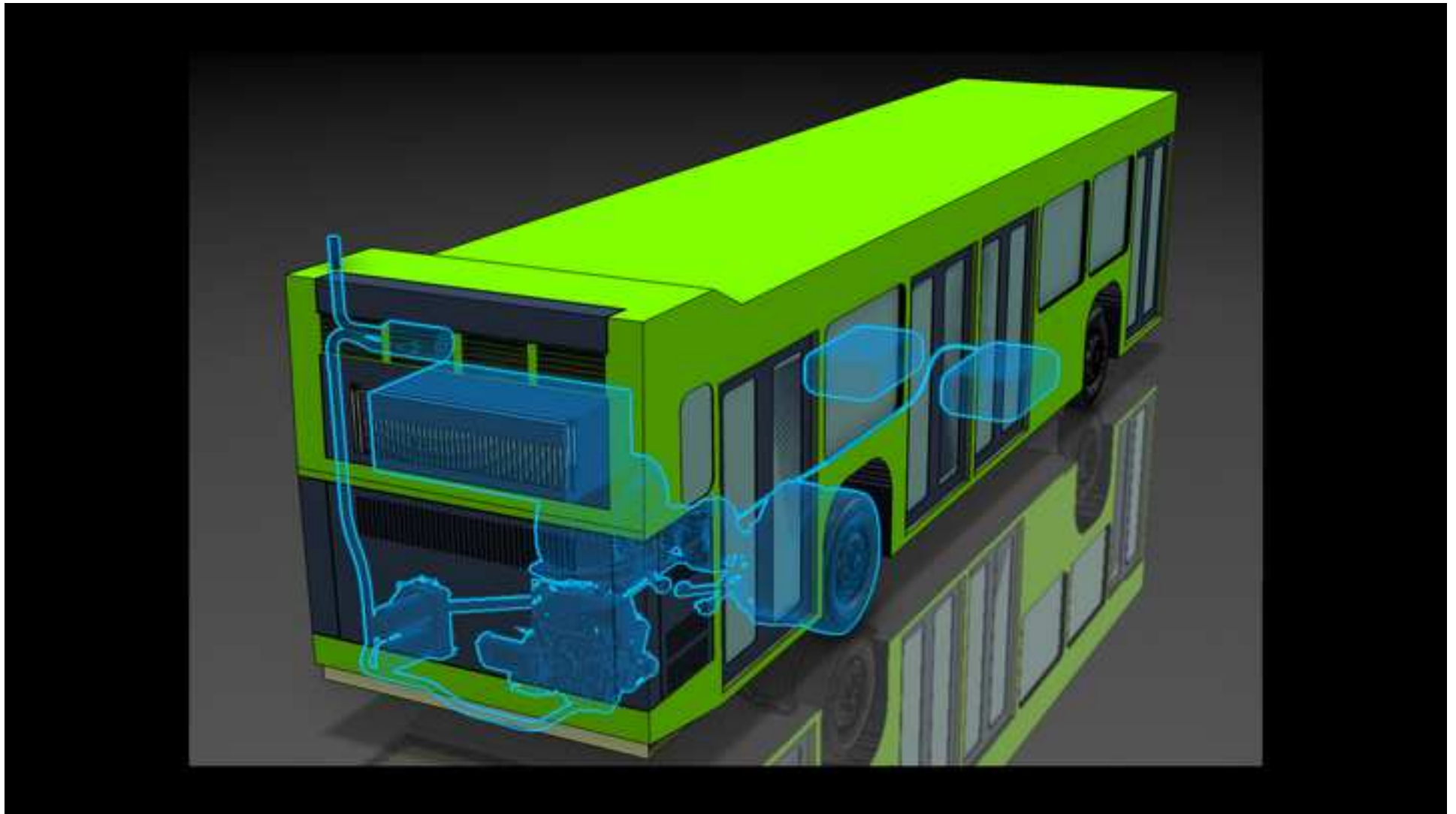


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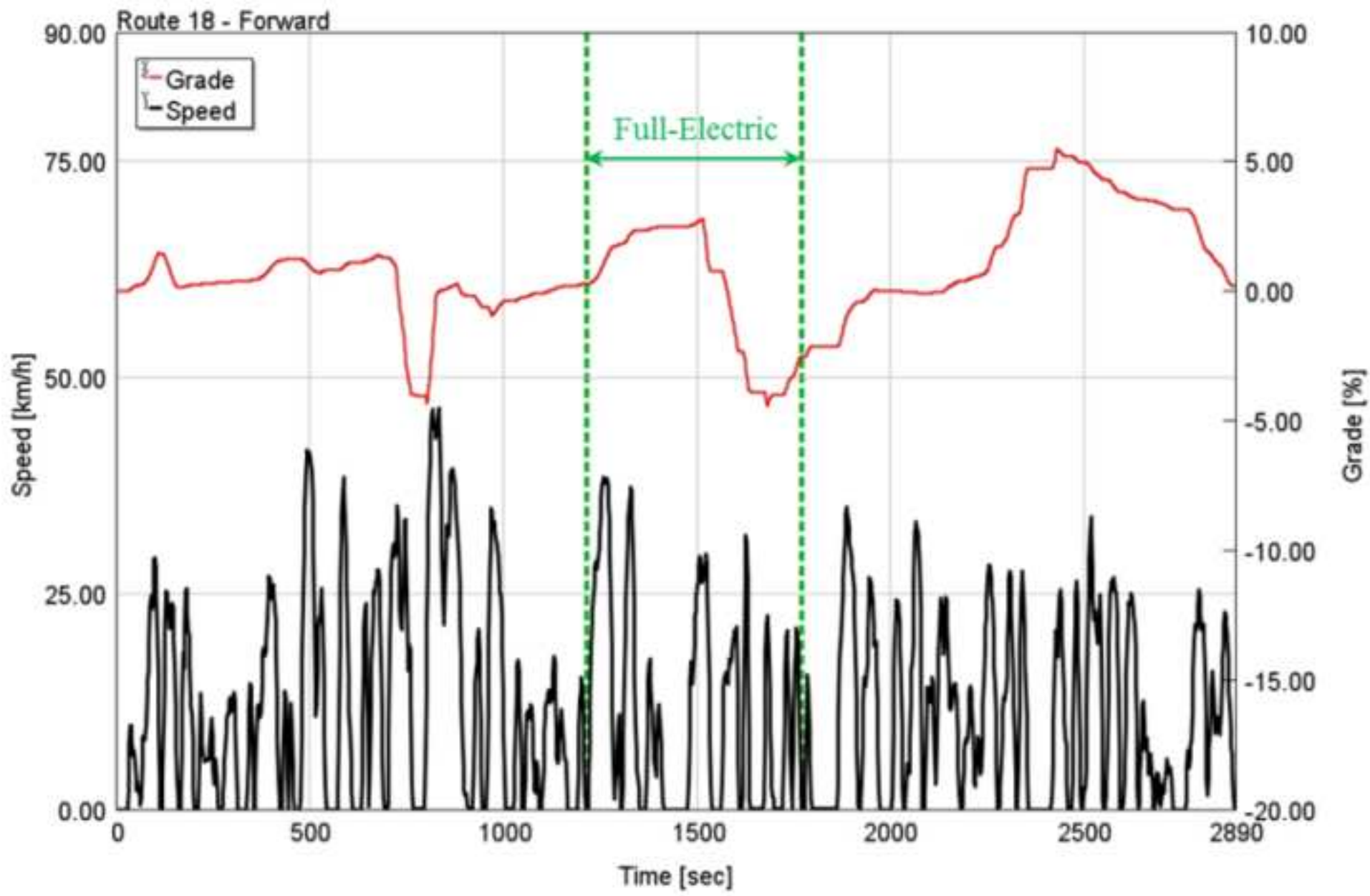


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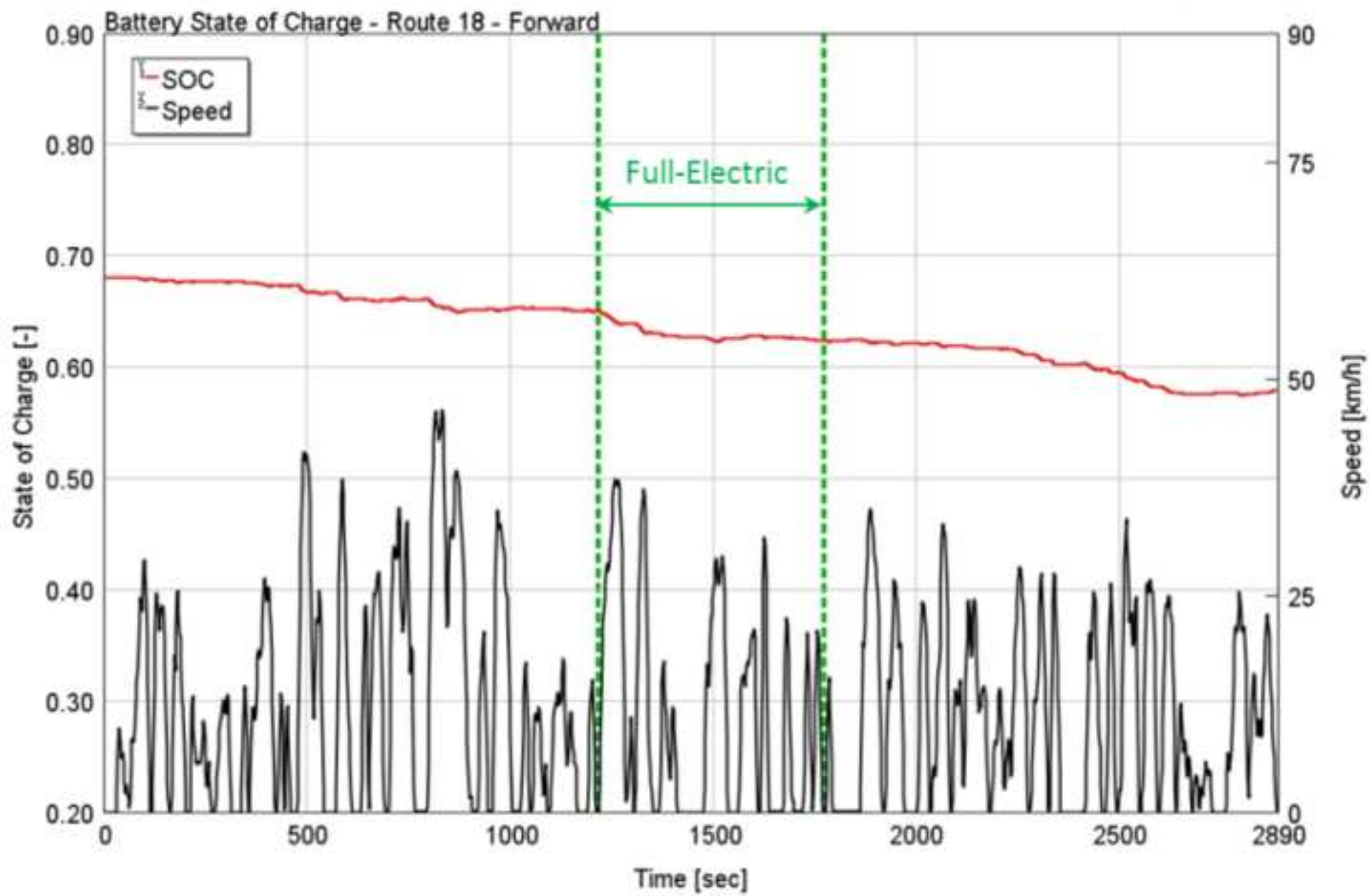


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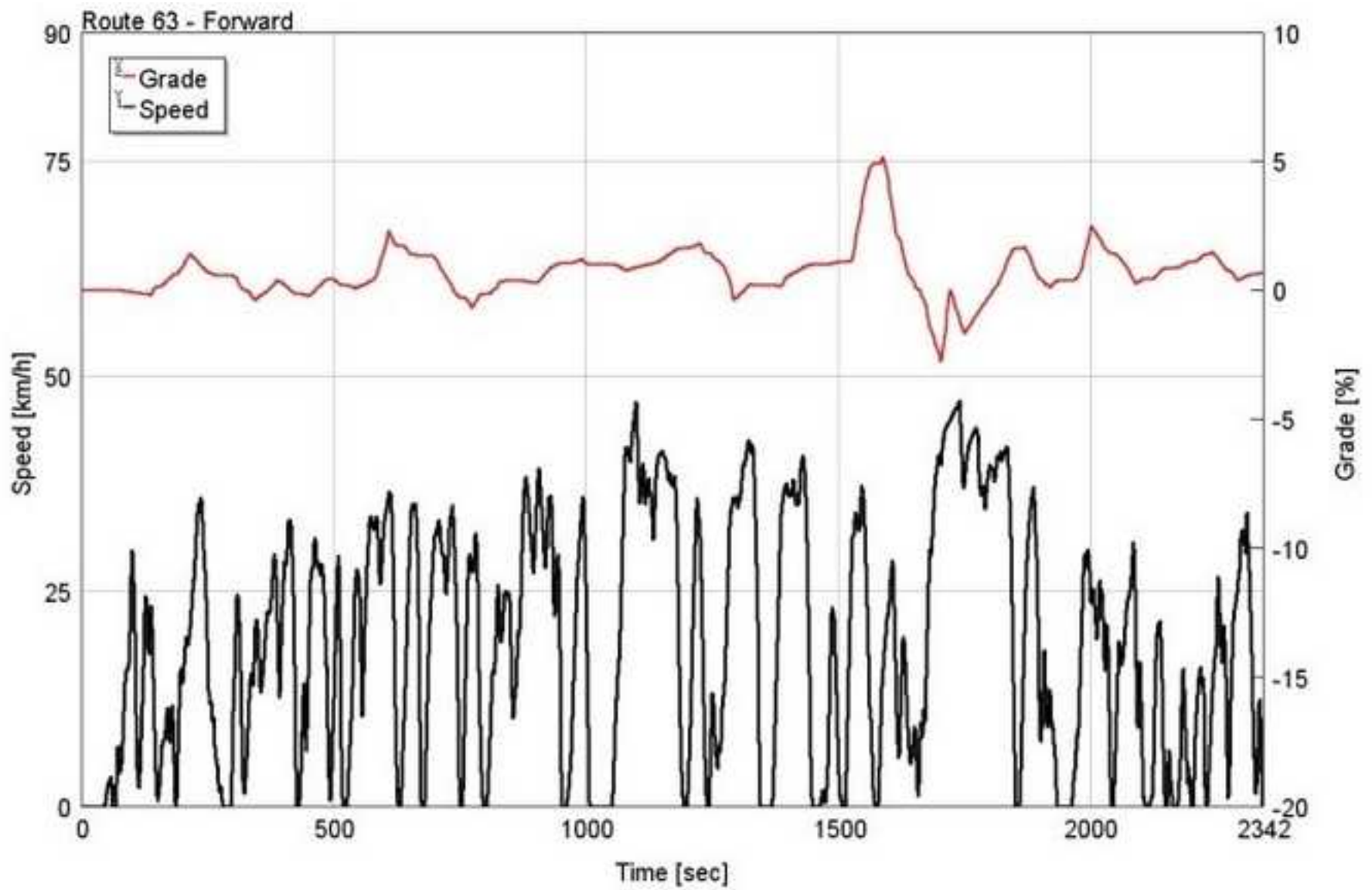


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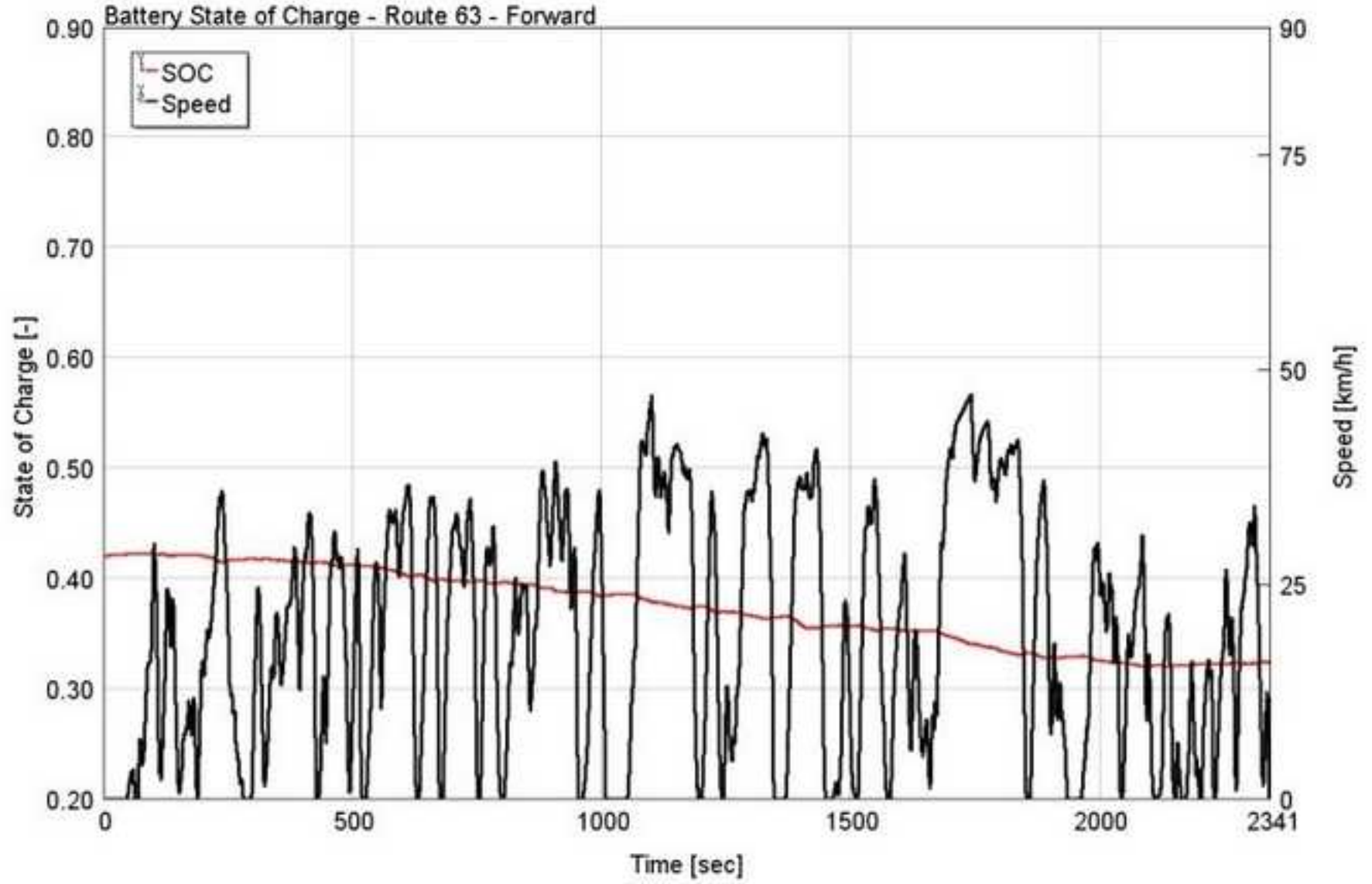


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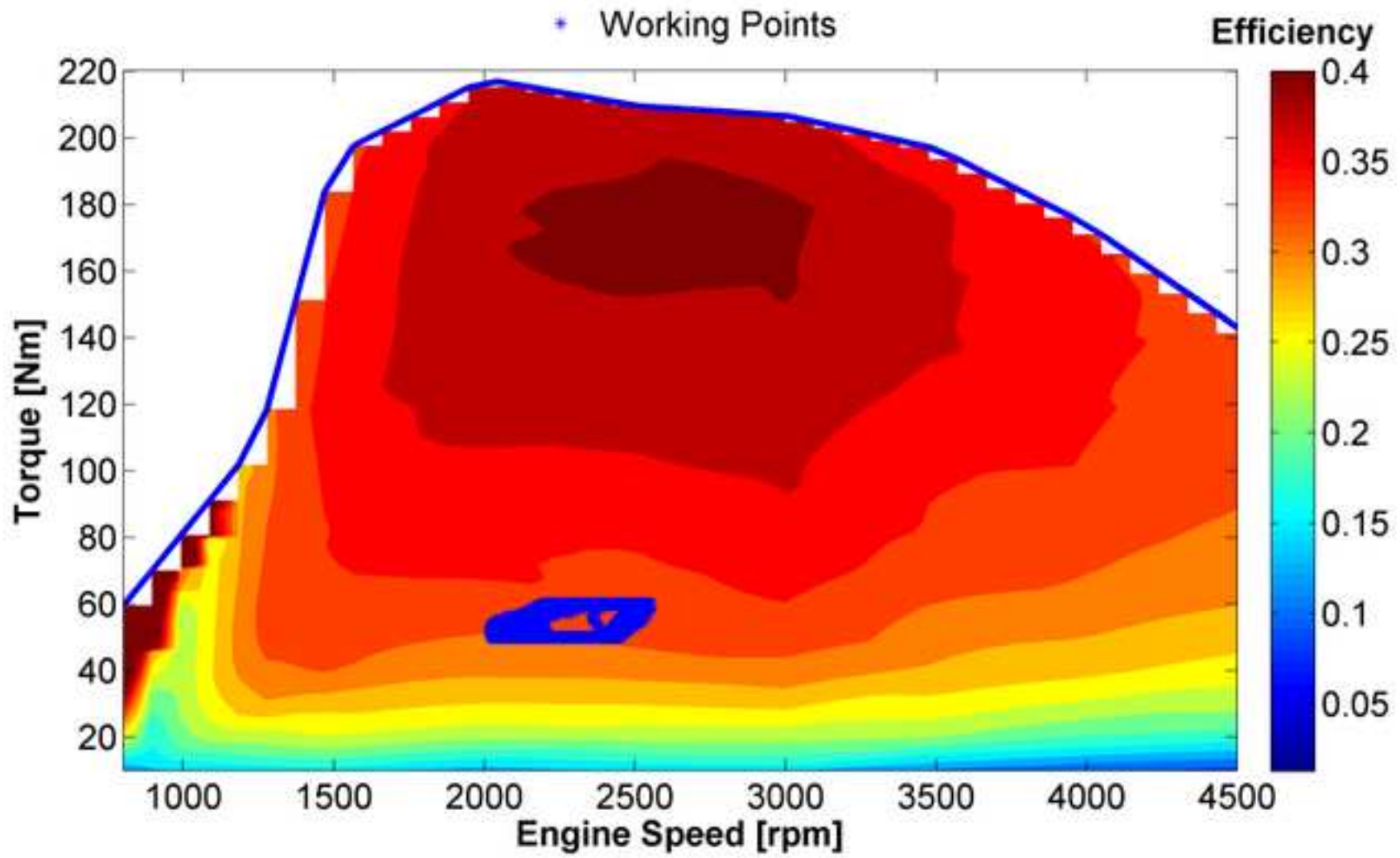


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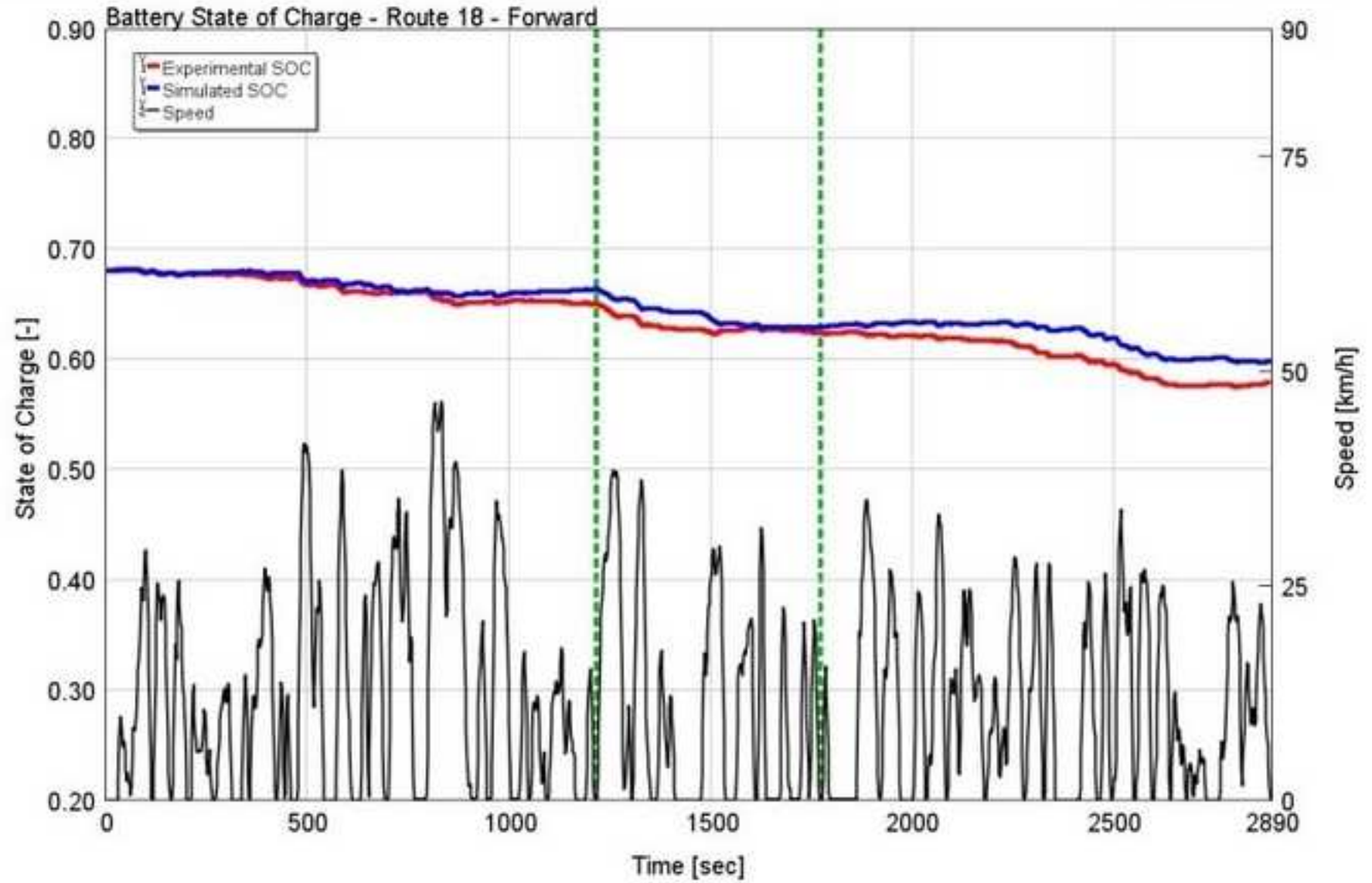


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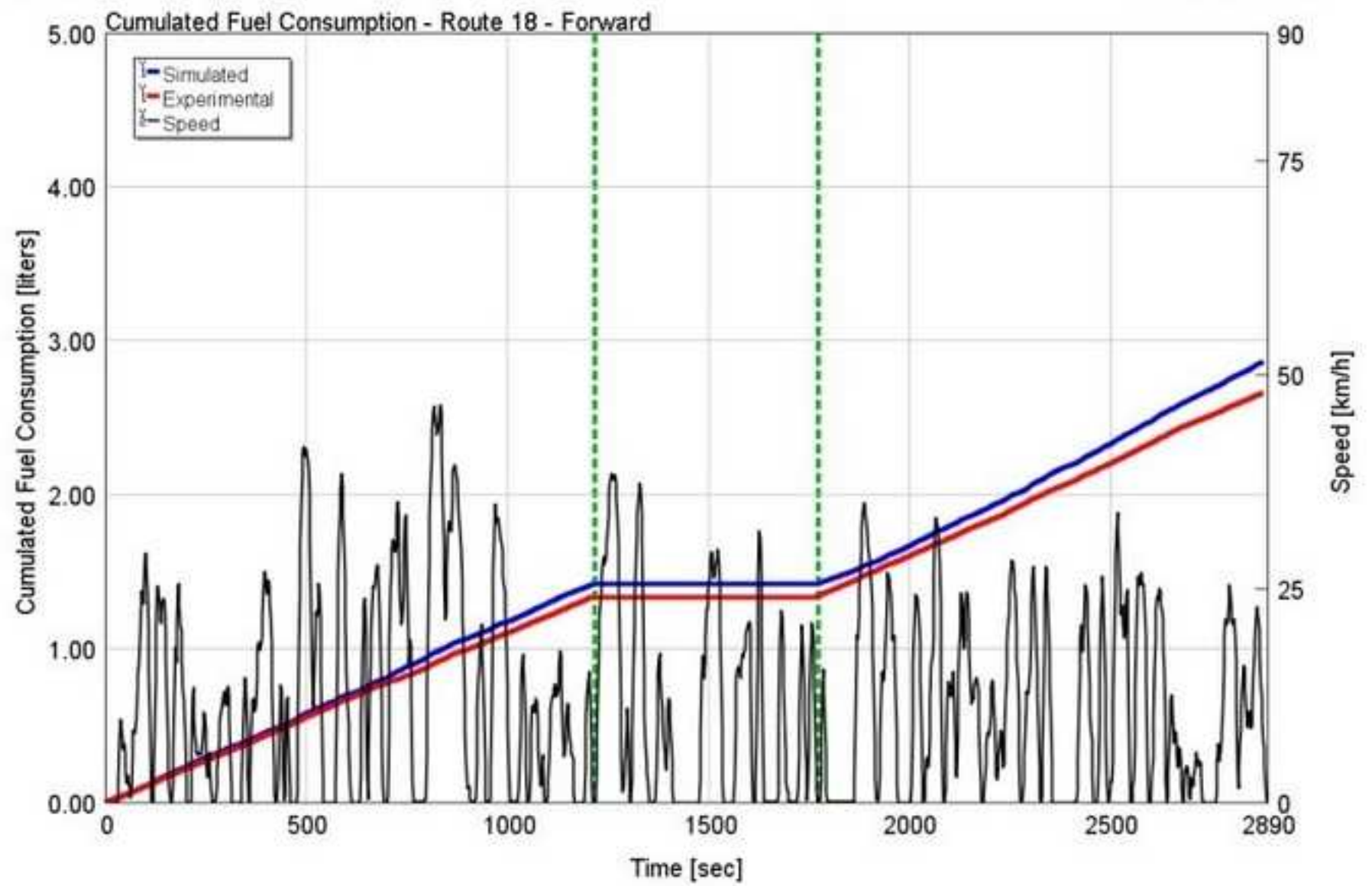


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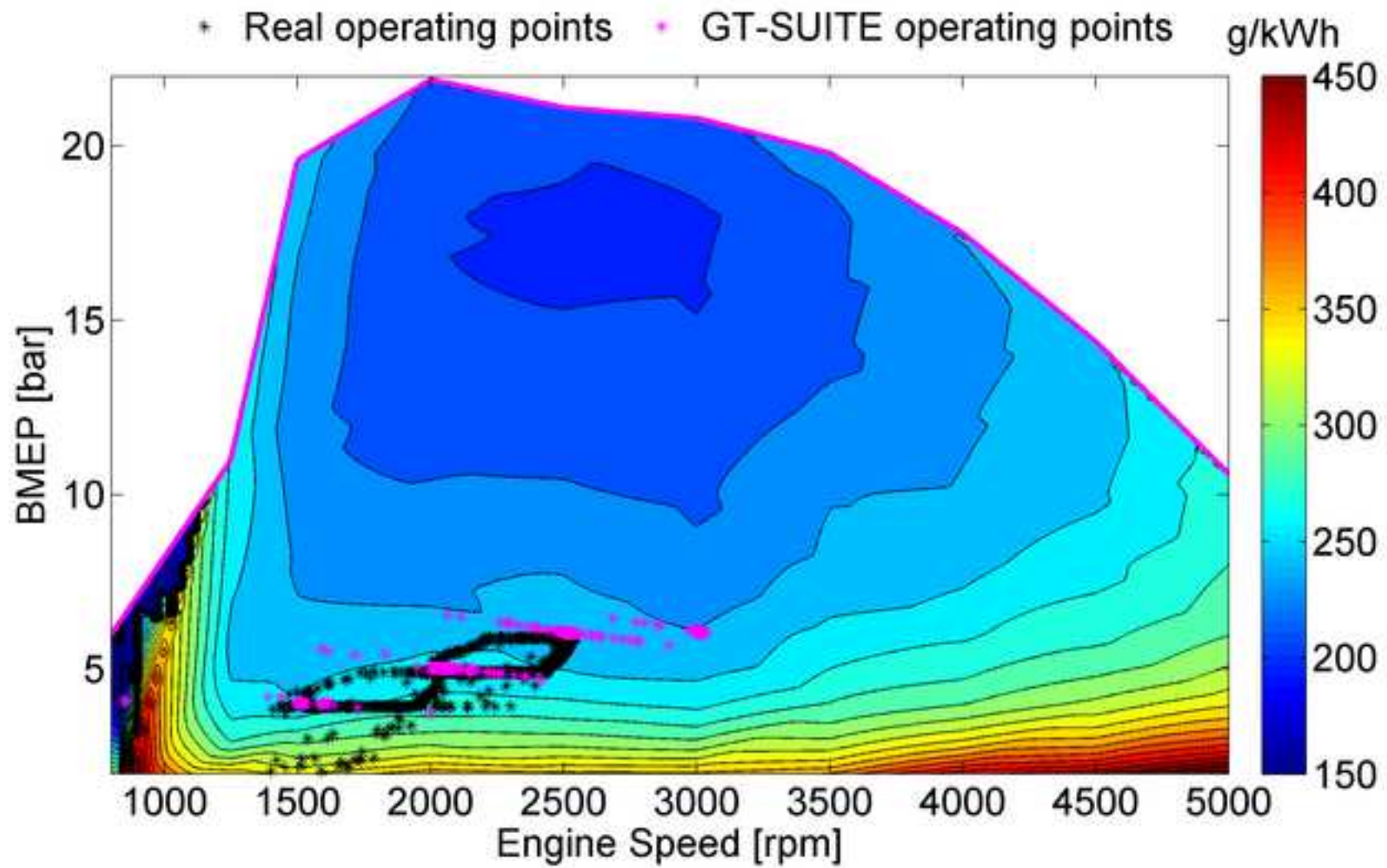


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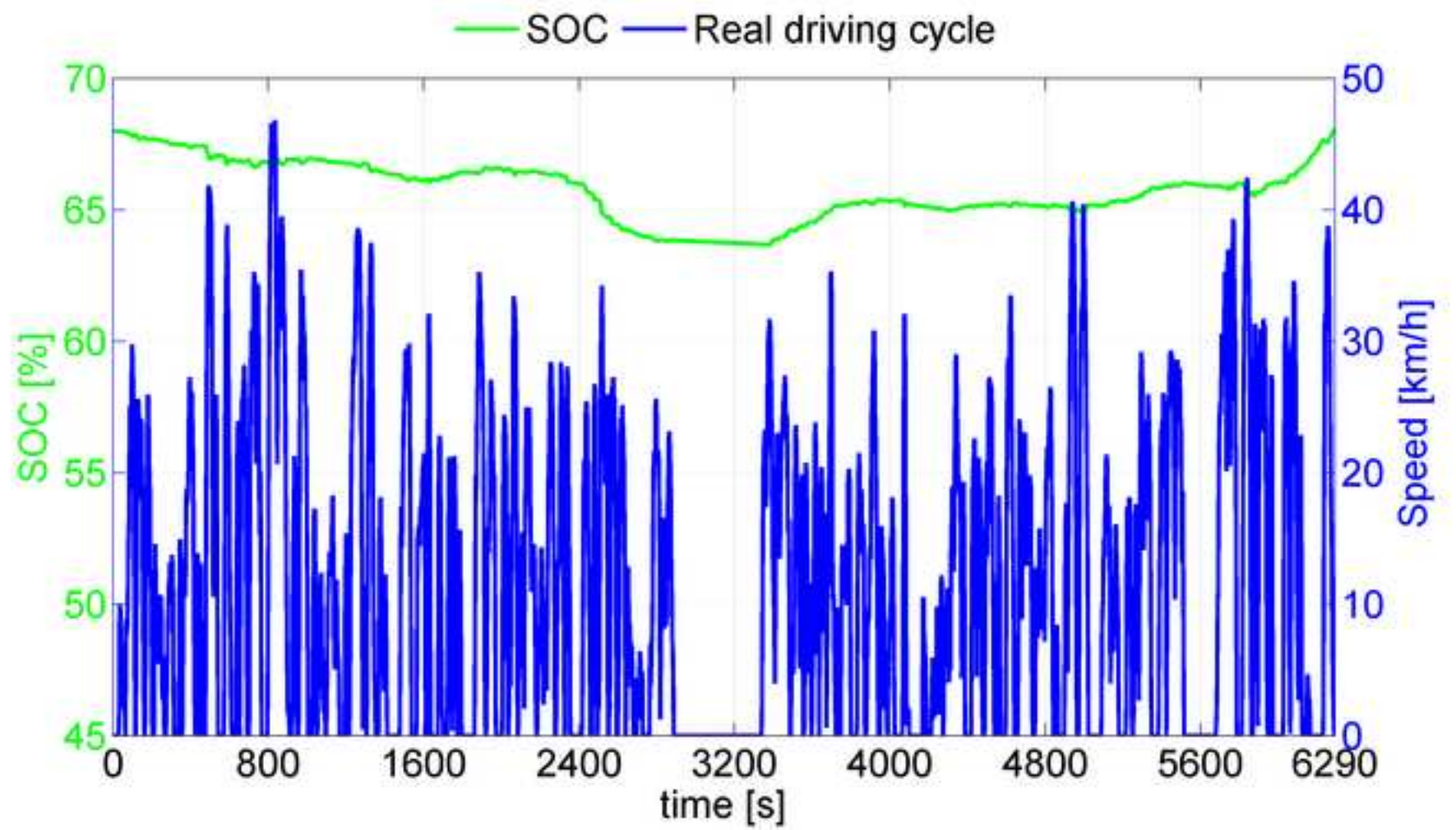


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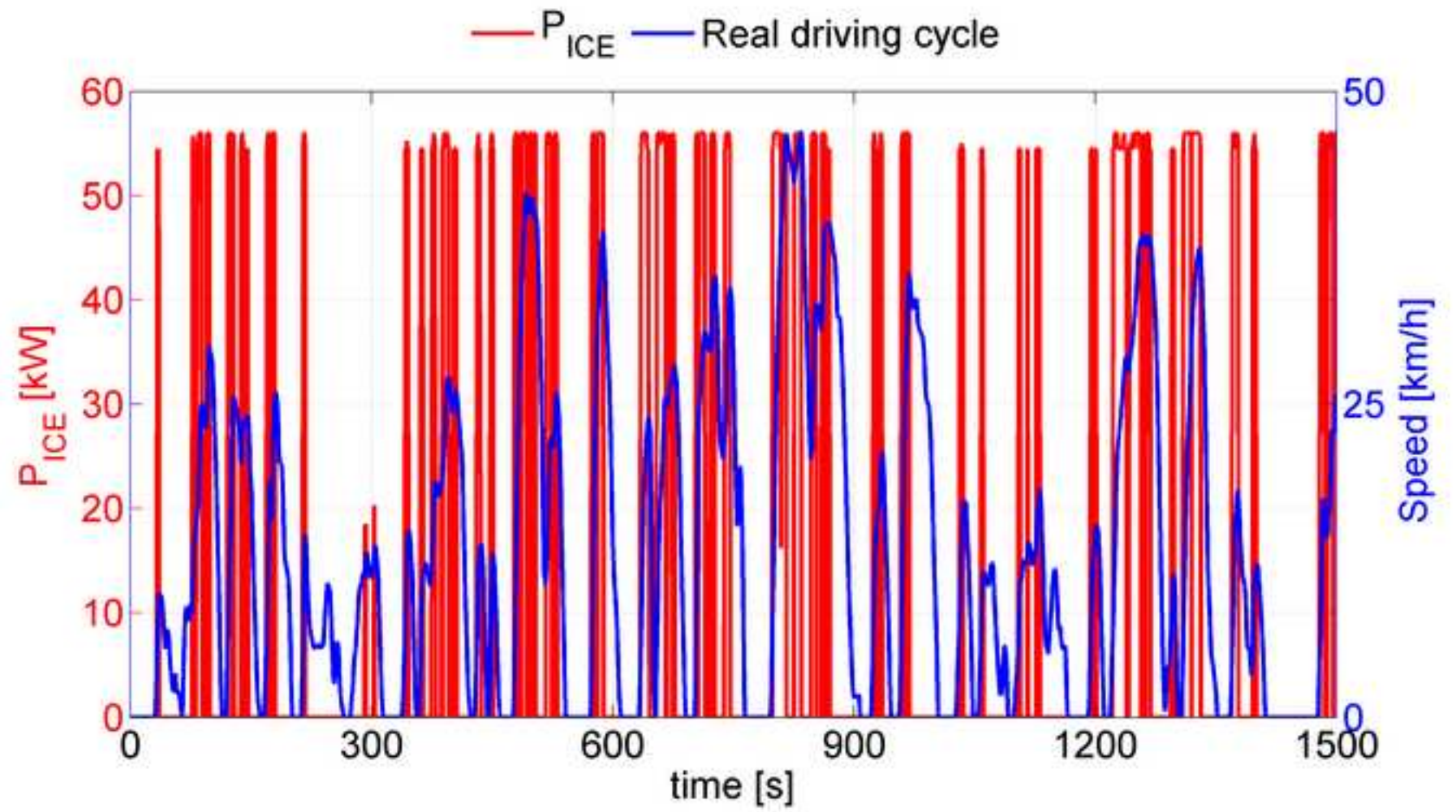


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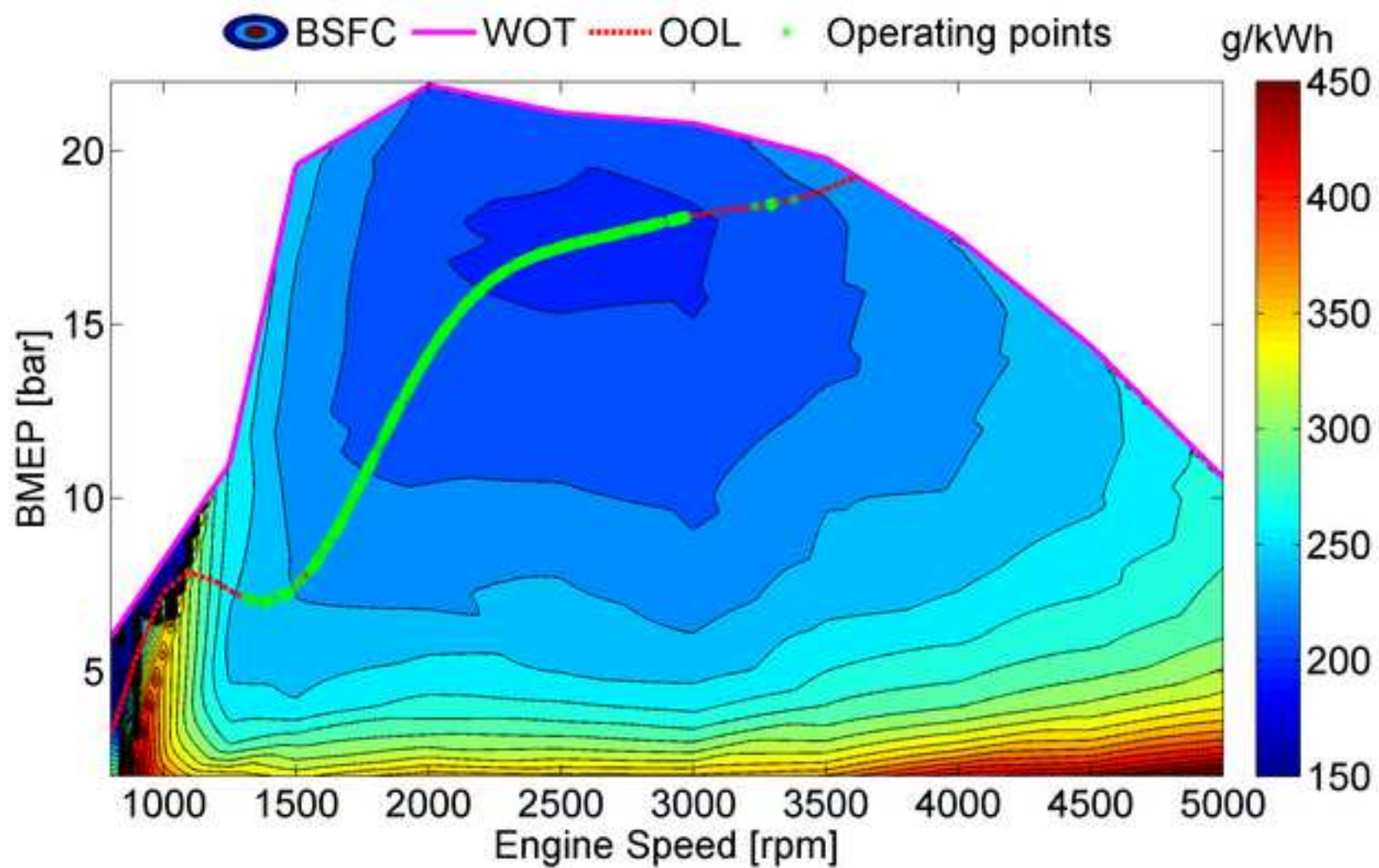


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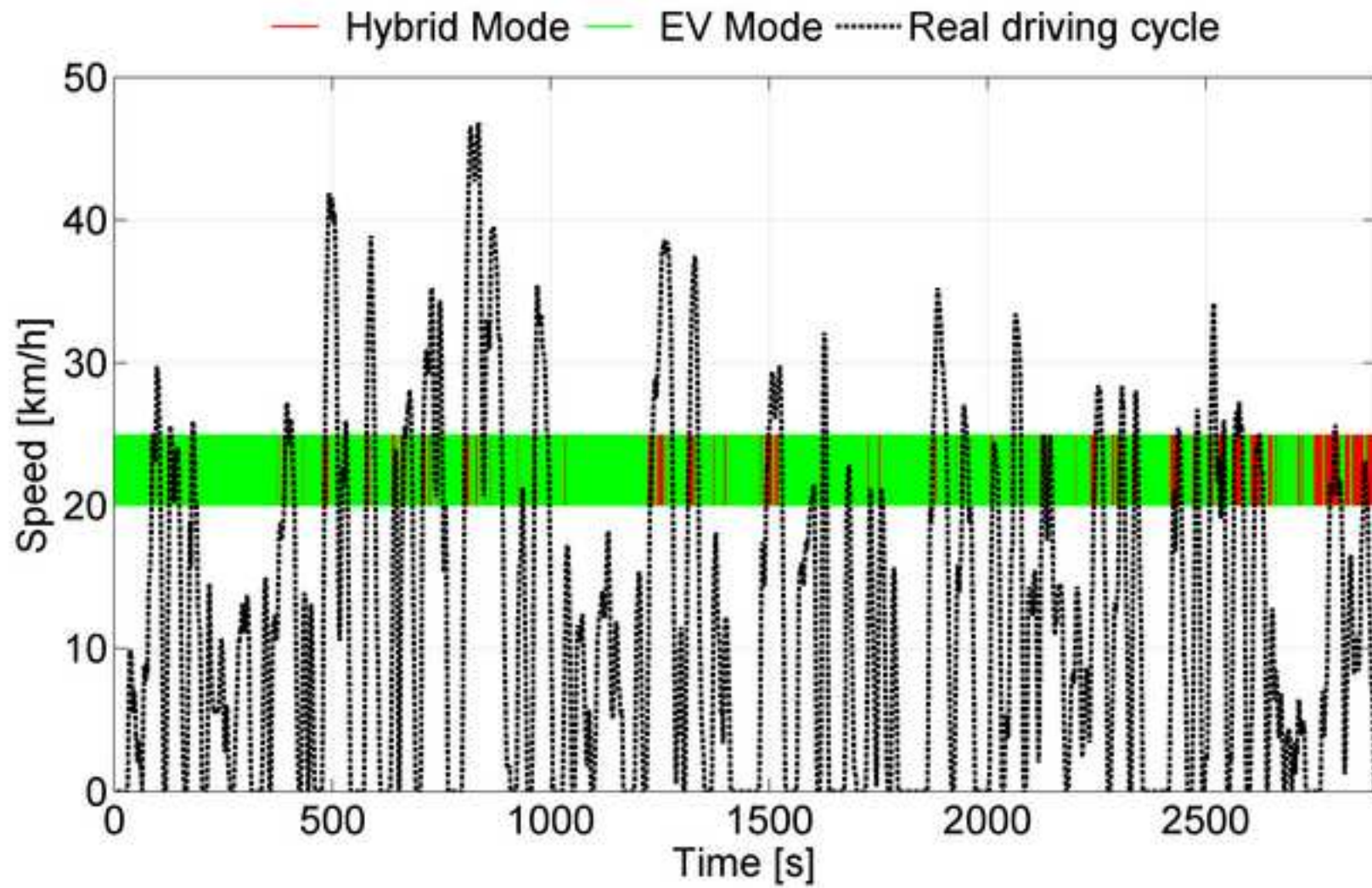


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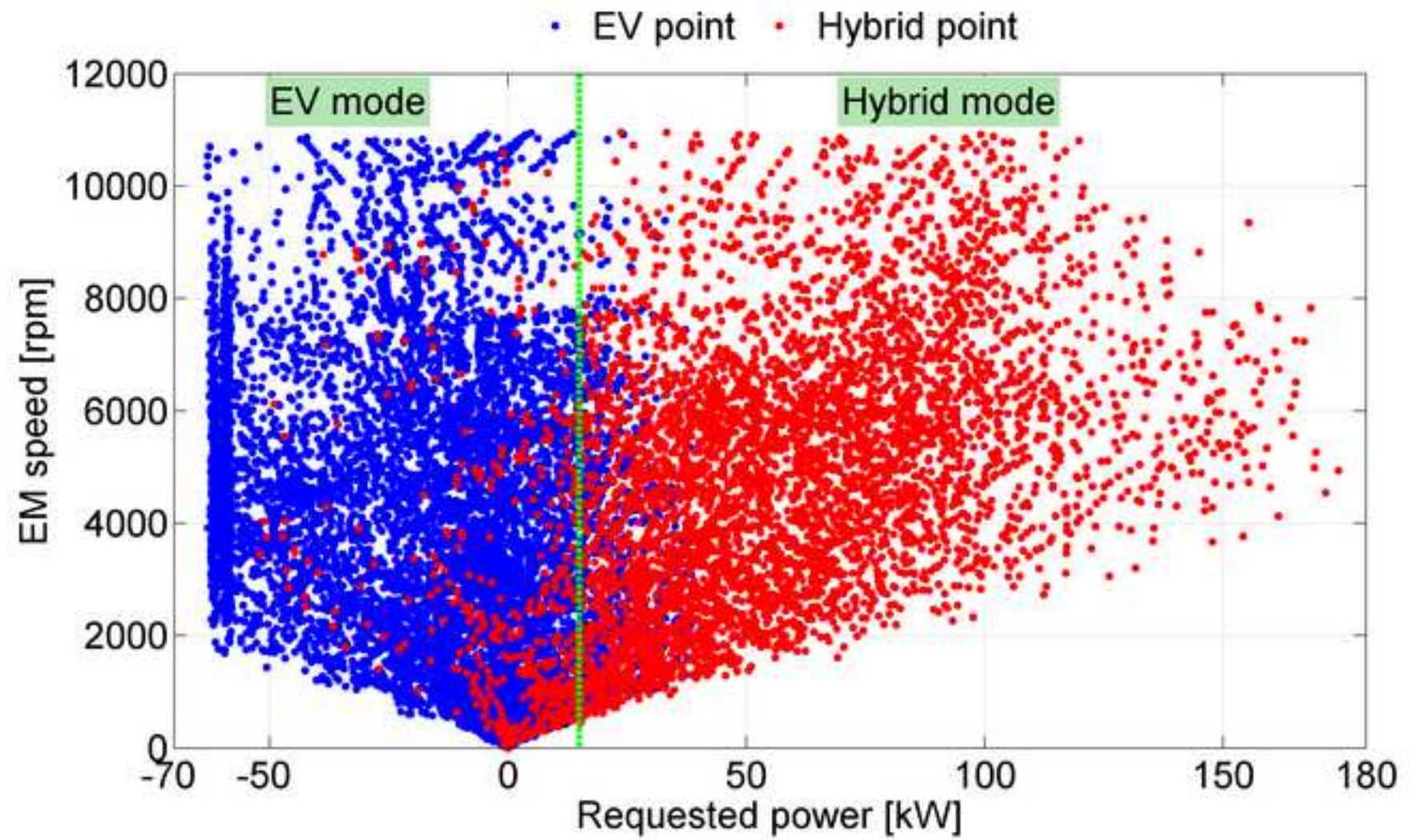


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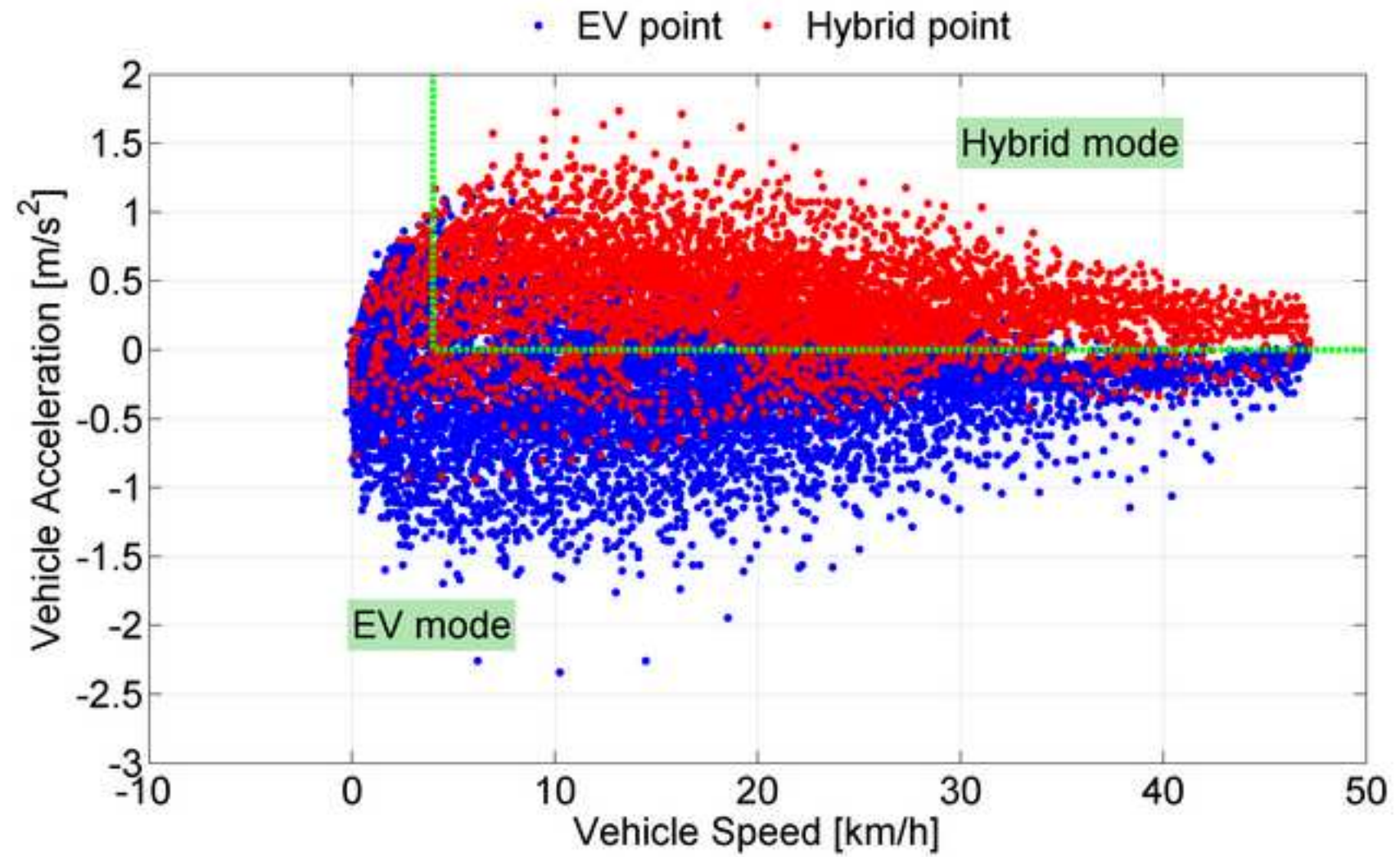


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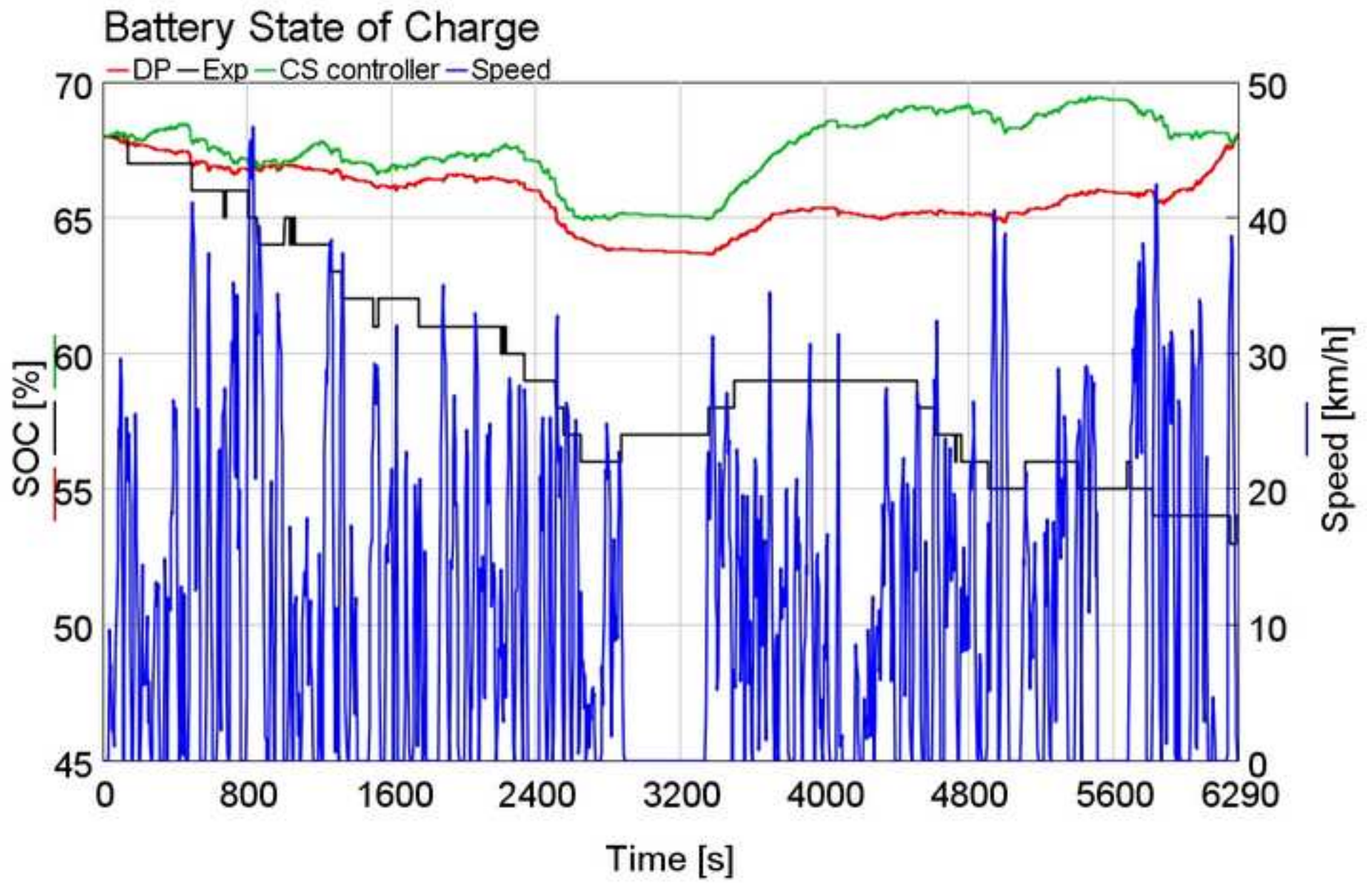


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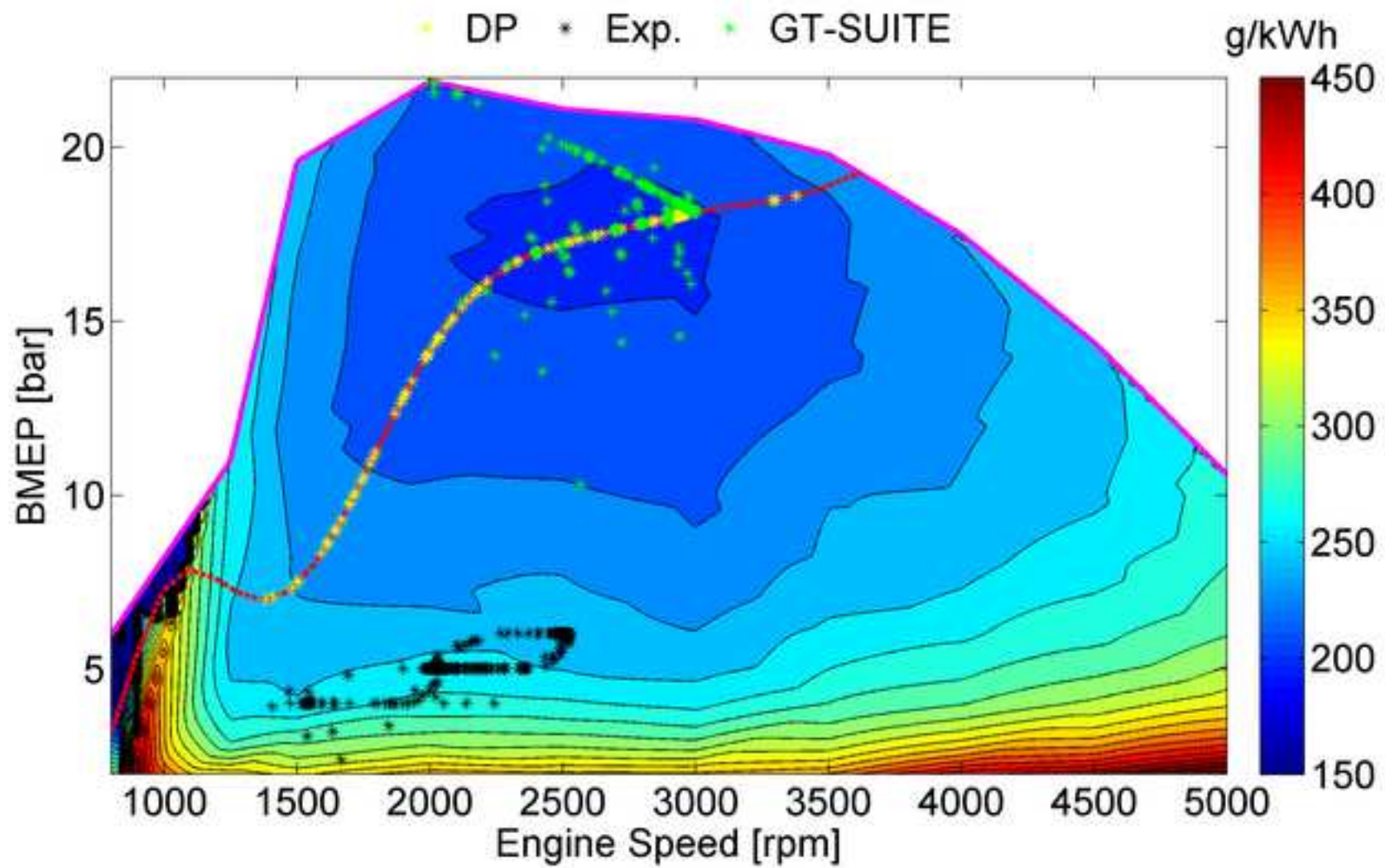


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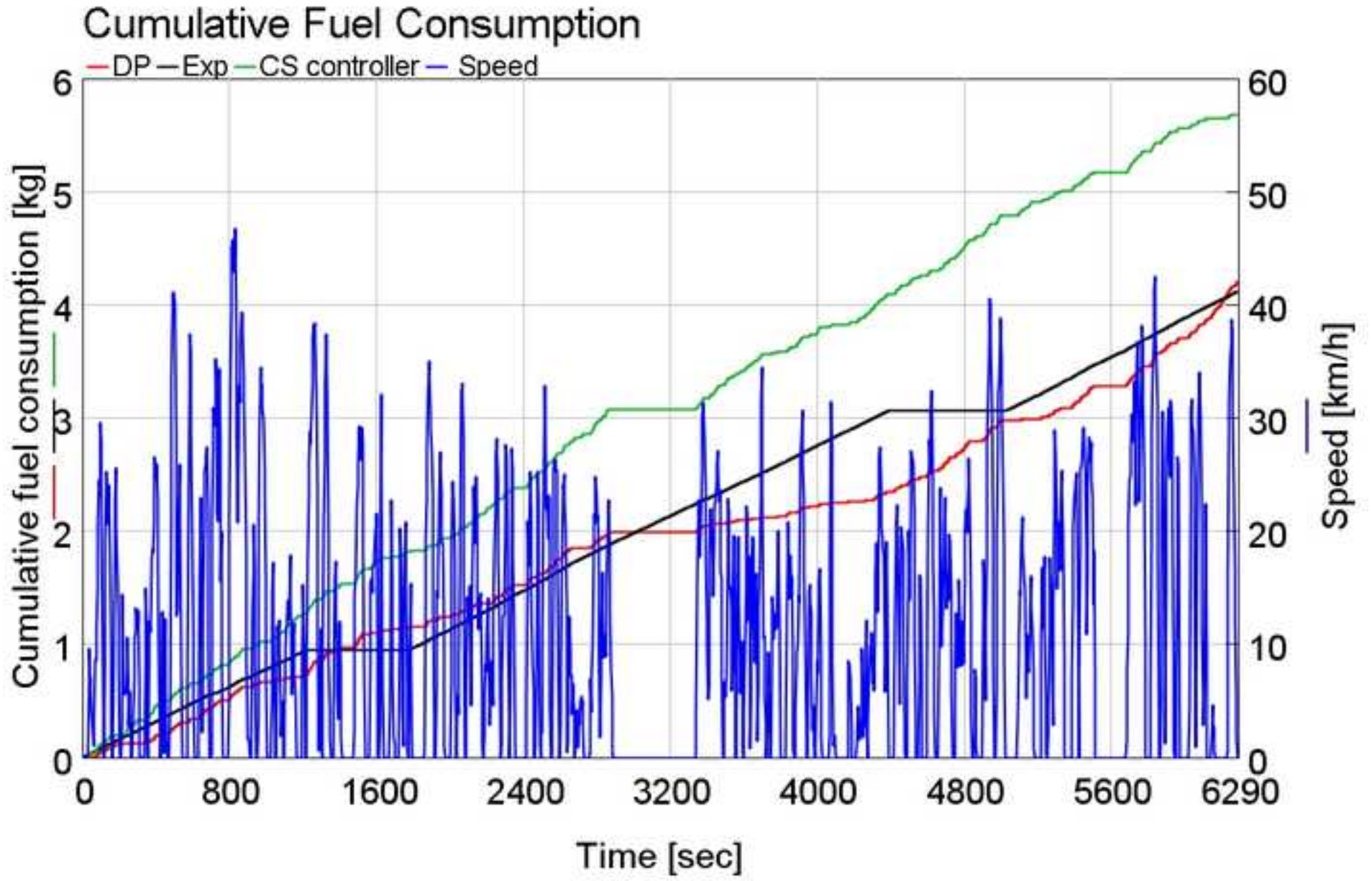


Table 1. TURBOCITY UR-GREEN data

Dimensions [mm]	12000x2500x3130 (LxWxH)
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]	$0.006+0.23 \times 10^{-6} \times V^2$ (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 ($m_{\text{fuel}}\text{LHV}$) [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 ($m_{\text{fuel}}\text{LHV}$) [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

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 ($m_{\text{fuel}}\text{LHV}$) [kWh]	43.8
	HYBUS [g/km]	182
	HYBUS fuel energy ($m_{\text{fuel}}\text{LHV}$) [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

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14 15 16 17 **Abstract**

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

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

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

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

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

44 **Keywords**

45 Hybrid Electric Bus; CO₂ Emissions; Energy Cost.

46 **1. Introduction**

47 In a context of the global economic downturn, the high demand for sustainable
48 transportation and for cost reduction for transit agencies could meet halfway.
49 Indeed, fuel cost represents one of the most significant portions of transit agency
50 budgets (by way of example for the 2012 for the Turin Transit Agency fuel cost was
51 equal to 22% of sales proceeds [1]) and its reduction directly corresponds to a cut
52 of CO₂ emissions. As a consequence, bus hybridization offers an attractive option
53 in this direction and has the potential to significantly reduce operating costs for
54 agencies.

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

59 Although the best enhancement in terms of fuel consumption is usually reached by
60 means of powertrain architectures with high flexibility like Hybrid Electric Vehicles
61 (HEVs), to date HEVs had not been widely adopted due to their high costs related
62 mainly to the battery pack. Therefore, sometimes low cost hybridization solutions
63 such as for instance Hybrid Hydraulic Vehicles (HHVs), seem to be more attractive

64 even if they exhibit lower efficiency compared to equivalent electrified powertrains
65 [5].

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

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

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

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

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

95 The cost saving is estimated to be about 50% compared to a new conventional
96 diesel bus (for which a price estimate between 220-290 k€ can be made[16-17])
97 and about 60% compared to a new hybrid bus (for which a price estimate of about
98 350 k€ can be made [18-19]).

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

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

112 **2. HYBUS Development and Experimental Assessment**

113 **2.1. Powertrain Requirement Evaluation**

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

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

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

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

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

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

133

134 **2.2. Main HYBUS Characteristics**

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

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

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

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

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

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

176 **2.3. Testing Activities**

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

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

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

194

195 ***Pure Urban - Route 18***

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

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

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

219 route 18 for a conventional diesel bus will lead to more than 16 €, highlighting the
220 impressive savings of the HYBUS.

221 ***Urban & Suburban Mix - Route 63***

222 After the urban tests previously described, an urban & suburban mix was tested on
223 Route 63, which is representative of a commuter usage, with two urban sections
224 connected by a central suburban piece. The total length of the round trip is about
225 23.3 kilometers, with an average speed of about 19 km/h, and the grade profile
226 (with a peak of 5%), together with a real speed profile, is depicted in Figure 6. The
227 SOC depleting resulting from the trip is shown in Figure 7.

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

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

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

242 ***Compared “back-to-back” fuel consumption test***

243 In order to complete the assessment of the HYBUS performance also a
244 comparative “back-to-back” test was performed: a city route, the urban Route 48,
245 was performed with the HYBUS running first, immediately followed by a
246 conventional bus, so to have the same traffic conditions, measuring at the end the
247 overall fuel consumption of the two vehicles. Although the aerodynamic drag of the
248 second bus was affected by the HYBUS, for this comparison these effects could be
249 neglected, considering the low speeds reached during the test. The conventional

250 bus was a 12 meters long Scania CV AB Omnicity, selected among the newest
251 part of the Genoa Transit agency fleet. Both the vehicle were ballasted to reach
252 about 16 tons each.

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

257

258 **3. Numerical Simulation of the HYBUS**

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

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

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

272 **3.1. Model set up**

273 Computer simulations were carried out by means of a vehicle model developed in
274 GT-Drive [27-29], where the internal combustion engine and the electric machines
275 are represented through performance maps, which were experimentally measured
276 under steady state operating conditions. Hence, although system dynamics are
277 taken into account, the simulation model follows a “quasi-static” approach, because
278 engine and electric machines behavior is described by steady state maps. This
279 simulation approach has been demonstrated to be appropriate for the evaluation of

280 instantaneous fuel consumption of light-duty vehicles [30] over the most common
281 regulatory driving cycles, due to the moderate speed (typically between 0 – 130
282 km/h) and load transients which are usually prescribed, while the assessment of
283 the simulation accuracy for urban buses driving cycles has been discussed in
284 previous works of the research group, such as for instance in [31].

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

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

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

295 **3.2. HYBUS Model Validation**

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

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

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

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

310
311

3.3. HYBUS potential assessment through numerical simulation

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

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

330 4. Energy Management Strategy development

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

335 Usually, due to the a-priori knowledge of the mission profile and the high
336 computational requirements, Energy Management Strategies (EMS) optimization
337 cannot be performed in real-time on hybrid vehicles. Nevertheless, for urban buses
338 the mission profile can be known a-priori, at least to a certain extent, thus paving
339 the way to the development of "route-tailored" energy management strategies.
340 Therefore, a sub-optimal controller was developed based on heuristic rules, which
341 were determined on the basis of the analysis of the results obtained by means of
342 Dynamic Programming (DP) simulations. For this purpose, a forward and backward

343 trip, of a real driving cycle representative of a specific route of the Genova transit
344 agency was used.

345 **4.1. Dynamic Programming – Modelling Approach**

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

354 The energy management can be optimized through DP using cost functions
355 focused on different targets, such as for instance the minimum fuel consumption or
356 the minimum pollutant emissions over a certain cycle. In this case, since the simple
357 minimization of the fuel consumption is not a suitable target for a plug-in hybrid, the
358 cost function was defined aiming to minimize the overall CO₂ emissions, including
359 both emissions generated by the fuel burned by the ICE and the equivalent
360 emissions due the electrical energy consumption from the battery (which will have
361 to be recharged from the grid) along a real driving cycle. Previous studies [35]
362 have highlighted that this approach will lead also to the minimization of the total
363 cost of the fuel and of the electricity. Therefore, the cost function to be minimized
364 can be written as:

$$365 \quad \min J = \int_0^T \left(\dot{CO}_{2f}(t, u(t)) + \dot{CO}_{2e}(t, u(t)) \right) dt \quad (1)$$

366 with:

$$367 \quad \dot{CO}_{2f} = \frac{\mu_{CO_2}}{\mu_{fuel}} \cdot \dot{m}_f \quad (2)$$

$$368 \quad \dot{CO}_{2e} = k_{CO_2} \cdot SoC \cdot E_{Batt, Norm} \quad (3)$$

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

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

383 Finally it should be pointed out that, after removing the constraints applied to the
384 ICE during the experimental tests to preserve the first prototype of the HYBUS,
385 was now free to operate on its Optimal Operating Line (OOL), as shown in Figure
386 14, corresponding to the minimum Brake Specific Fuel Consumption (BSFC).

387 **4.2. Dynamic programming – Results & Rule Extraction**

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

392 The SOC variation determined by the DP are shown in Figure 12 over the entire
393 real driving cycle: it can be clearly seen that, with an initial value of the SOC equal
394 to 0.68, the DP proved to be able to guarantee the charge sustainability. A zoomed
395 in portion of the driving cycle is also reported in Figure 13, showing the requested
396 power from the internal combustion engine: the most frequently requested power is
397 about 56 kW, while the working points are exclusively located on the OOL as
398 shown in Figure 14. Finally, the choice between the two different operating modes,
399 i.e. pure Electric Vehicle (EV) and Series Hybrid mode, operated by the DP is

400 shown in Figure 15: it is pretty evident that series hybrid mode is mainly exploited
401 when the power demand is high, e.g. during strong accelerations.

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

412 **4.3. Rule based strategy performance evaluation**

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

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

420 The new controller was able to manage the SOC and guarantee the charge-
421 sustainability (see Figure 18). On the other hand, it is worth to be noticed that
422 during the experimental test on the field in Genova the final SOC decreased to
423 54%. Consequently, the electrical energy consumed over the real driving cycle was
424 about 14 kWh, with a specific electricity consumption of 0.75 kWh/km.

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

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

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

441

442 **5. Conclusions**

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

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

449 The main outcomes of the tests were the followings:

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

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

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

466 **6. Acknowledgements**

467 The authors would like to gratefully acknowledge the valuable contribution of
468 Pininfarina, and of the transit agencies of the cities of Turin and Genoa.

469

470 **7. Funding**

471 This work was financially supported by the Regione Piemonte in the framework of
472 the AMPERE project.

473 **8. Definitions and Abbreviations**

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

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

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